PYROCLASTIC GEOLOGY OF OAHU

BY

CHESTER K. WENTWORTH

BERNICE P. BISHOP MUSEUM

BULLETIN 30

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INTRODUCTION

SCOPE AND PURPOSE

The southeast end of the island of Oahu, Hawaii (fig. 2), has been the scene in relatively recent geologic time of a series of secondary pyroclastic eruptions. These have taken place around the coastal margin and the resulting cones have increased the land area of the island by many square miles and given to the coastal region its most salient physiographic features. The present investigation is concerned with this series of craters, some twenty in number, included within an area of about sixty square miles. It is designed as a contribution to historical geology, to volcanology and to the knowledge of sedimentation.

In the volcanic activity by which the Hawaiian islands have been formed, explosive eruptions have played an insignificant part when considered from the quantitative standpoint. Locally, however, and in consonance with the principle that pyroclastic action is frequently characteristic of the waning stages of volcanism, explosive eruptions have interrupted the quiet of established sedimentary processes and have produced features which dominate the surrounding topography. In the intimate association which exists between the pyroclastic materials and certain small contemporaneous lava flows there is opportunity for learning something of the mechanism of volcanic action and of the condition of the igneous magma immediately prior to expulsion.

It is in connection with sedimentary processes, however, that the craters of Oahu have their most significant application. Igneous rocks have been formed both by quiet extrusion and by explosive expulsion from the same magma. They have been subject to immediate attack by nearly all the known agents of weathering and the resulting debris has been carried and sorted by nearly every known agent of transportation. Deposits have been formed involving nearly every combination of igneous derivatives and marine organic constituents and now lie, some consolidated and others unconsolidated, for the most part within a few hundred yards of their

igneous source. The rock cycle, though lacking the completeness and perfection attained by long sustained action in continental areas, is here exemplified with unusual clarity particularly with reference to the alteration of basic igneous rocks in low latitudes.

An attempt to prepare a general statement of the characteristics and mode of formation of coarse sedimentary rocks and related materials led to realization of the great dearth of detailed information on pyroclastic rocks, in regard to their areal development, their origin and their petrography. For the most part the pyroclastics have been treated incidentally in connection with the study of igneous masses. In their mode of deposition and their consequent widespread incorporation in stratified sedimentary deposits, the pyroclastics are best studied by areal and stratigraphic methods, a requirement not always met in the few studies which are available. It is primarily as a contribution to sedimentary geology that this report is presented.

METHODS OF STUDY

Field work was carried on during the last four months of 1923, and parts of January, February, March, June, and July, 1924. The methods adopted are those usual to stratigraphic and structural geology. Determinations of structure were based almost exclusively on numerous readings of dip and strike. The strata of the pyroclastics, though usually of notable uniformity in any one outcrop, are subject to such variation laterally that correlation by lithologic characters, even throughout the limited extent of a single crater mass, is not feasible. Fortunately, outcrops are numerous owing to the naked character of the crater slopes and to the vigorous action of waves around the coastal margins, where there is a magnificent display of the features wrought by marine abrasion. In the course of field work a considerable series of specimens was collected, representing not only the pyroclastic rocks and associated lava rocks but also the numerous and diverse sedimentary derivatives. (See pp. 112-120.) Considerable attention was given to current physiographic processes, especially those of the coast, and the resulting conclusions are in part presented in this report and in part in briefer contributions on special subjects.

In the laboratory examination of collected specimens, attention has been given to the microscopic study of thin section and detrital minerals and an effort has been made to learn the salient physical properties such as shapes of particles and mechanical composition of the loose detrital materials and density and porosity of the indurated rocks. This procedure has been followed because of the relative dearth of geophysical data of this nature on the sedimentary rocks and the even more notable lack of data on the

pyroclastic rocks. In such work it is impossible to decide in advance the properties which are to be determined and any attempt to apply blindly any series of tests to all specimens is not only wasteful of time but may yield misleading information. Rather must the student select the significant tests and determinations with reference to each specimen and compare the results with similar results from specimens of the same sort.

ACKNOWLEDGMENTS

The opportunity to carry on the present study was provided by Yale University and Bernice P. Bishop Museum. A supplementary study on the island of Lanai was made possible through the generosity of the Hawaiian Pineapple Company.[1] Several other institutions have given valuable assistance. Laboratory space and equipment at the University of Hawaii was made available. The United States Geological Survey furnished instruments and other field equipment, and through its district topographic and hydrographic offices in Honolulu, in charge of A. O. Burkland and E. D. Burchard, respectively, was of frequent assistance in other ways. The detailed study of materials collected in Hawaii was carried on chiefly at the State University of Iowa, where considerable special equipment and service were provided. In the course of the field work, many residents of Honolulu and vicinity provided transportation and other assistance. Special mention is made of Professor Harold S. Palmer of the University of Hawaii, without whose aid and friendly counsel in matters both technical and practical, this study could scarcely have been completed in the present form. Dr. A. A. Pegau of the University of Virginia made the final examination of a considerable part of the thin sections and detrital materials. (See pp. 104-120.)

[1] Wentworth, Chester K., The geology of Lanai: B. P. Bishop Mus. Bull. 24, 1925

OUTLINE OF THE GEOLOGY OF OAHU

LOCATION AND SIZE OF OAHU

Oahu is about 40 miles long in a direction N66°W from Makapuu Head to Kaena Point, about 26 miles broad in a direction S15W° from Kahuku Point to Barbers Point, and has an area of 598 square miles. The general shape of the island is trapezoidal with the two nearly parallel sides extending in a northwest-southeast direction. The coast line is somewhat irregular and indented. (See sketch map, fig. 1.)

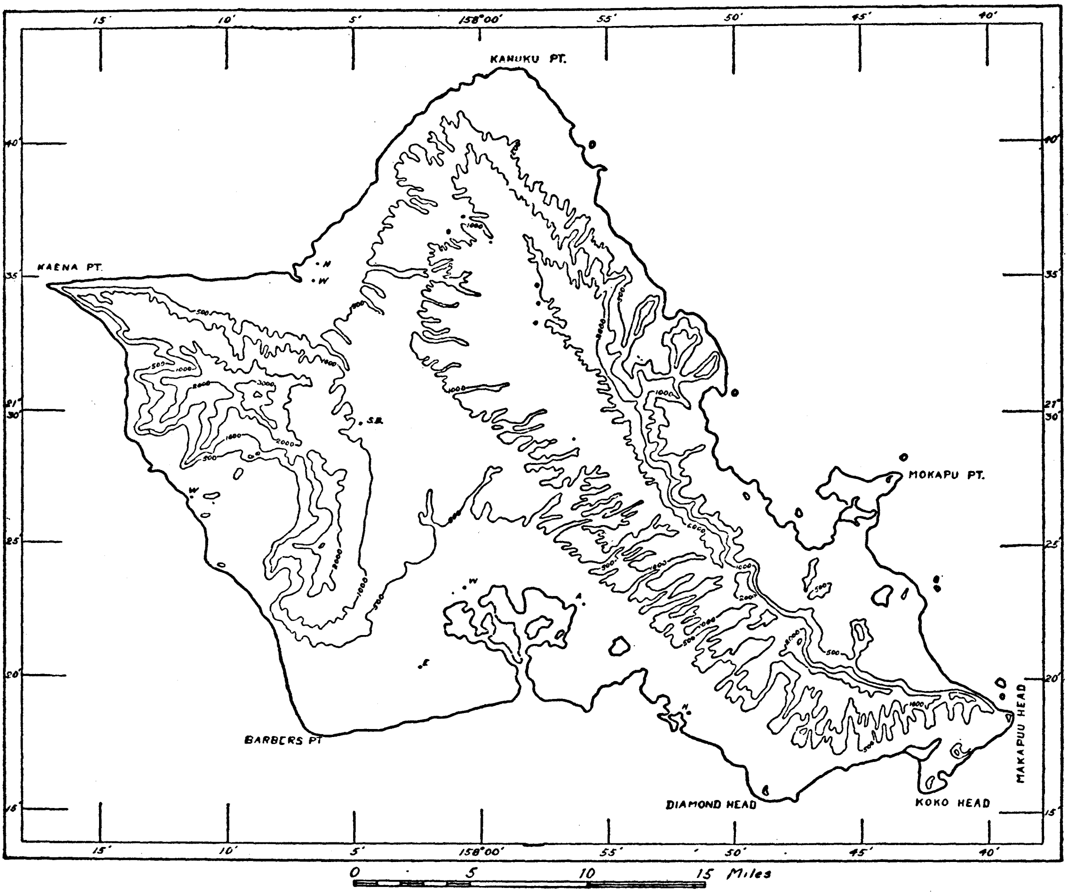

FIGURE 1.—Map of Oahu showing topography by generalized contours. Intervals 2,500 and 1,000 feet.

Oahu is situated on a linear elevated portion of the sea bottom which has a general northwest-southeast direction and from which all the Hawaiian islands rise (fig. 2). Between Oahu and Molokai, which lies about 27 miles southeast of Oahu, the depth of water in most places is less than 300 fathoms, only a relatively narrow channel reaching a maximum depth of somewhat less than 400 fathoms. Northwestward, the nearest island, Kauai, is 72 miles distant. For more than half of this distance the depth of water is less than 500 fathoms. The maximum depth, about 1900 fathoms, is at a point considerably nearer Kauai than Oahu. Along most parts of the northwest and northeast coasts of Oahu the 1000 fathom line is

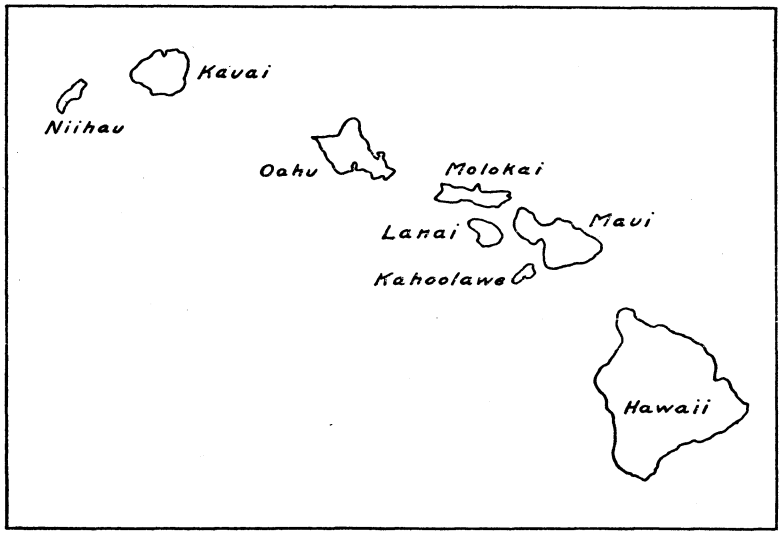

FIGURE 2.—Sketch map showing the eight principal Hawaiian islands.

located about 20 miles offshore; the 300 fathom line, 7 to 8 miles out. Southeast and south of Oahu the ocean has a general depth of 300 to 400 fathoms for 20 to 30 miles seaward and the bottom configuration is irregular. The southwest coast is bordered by the most precipitous submarine slopes, the sea bottom reaching a depth of 1000 fathoms in not over ten miles with a nearly continuous slope from the shore to this depth. The greatest depths found in this section of the Pacific include 2700 fathoms about 60 miles north of Kaena Point, 2500 fathoms about 40 miles south of Barbers Point, and 3000 fathoms 80 miles northeast of Makapuu Head. These distances are measured to the extreme depths of the surrounding ocean and not in such a way as to find the steepest slopes. The depths are all 15,000 feet or more and are attained at rates equal to or greater

than 375 feet a mile. The declivity and extent of these slopes will be appreciated when it is stated that so far as known they are not equalled in these respects on any part of the North American Continent and probably in very few places on the land area of the globe.

GENERAL FORM OF OAHU

Stated in the simplest terms, Oahu consists of the eroded remnants of two principal volcanic cones which have merged along a northwest-southeast line forming a relatively low intermontaine saddle now somewhat extended and modified by the deposition of alluvium in the northwest and southeast reentrants. The broad outlines of configuration of the island are shown by generalized contours in figure 1. Both the northeasterly Koolau Range and the southwesterly Waianae Mountains have roughly arcuate forms, of which the convex sides are adjacent each to the other. Each consists of a very great number of thin basalt flows which dip generally outward along the radii of the arcs at angles of 5 to 10 degrees. The greater part of these great masses of basaltic rock consists of pahoehoe but they include small masses of aa and thin and quantitatively negligible lenses of tuff and agglomerate. Brief descriptions of the general features of igneous rocks of these ranges and more detailed statements made concerning local features have been presented by Dana,[2] Dutton,[3] Hitchcock,[4] and Cross.[5] As yet no areal geologic survey has been made of the island and the solution of many questions here raised must wait for the completion of such a study.

The curved crest of the Waianae Mountains is in general more than 2000 feet in elevation; it rises in a number of places to 3000 feet and culminates in Puu Kaala at 4030 feet. The Koolau Range reaches 2000 feet over a large part of its length but has fewer high summits and culminates in Puu Konahuanui at 3105 feet. It has generally been considered that the Waianae Mountains are much the older of the two and were subjected to extensive erosion, both marine and fluvial, during the time that they were exposed to the trade winds before the building of the Koolau Range. Hitchcock found evidence that the Koolau lavas were extruded against the eroded surfaces of the Waianae Mountains.

One other feature of the ranges is of primary importance in considering the origin of the Oahuan land mass. This is the series of gently sloping triangular facets on the lower interstream spurs of the flanks of both

[2] Dana, J. D., U. S. Exploring Expedition (Wilkes), vol. 10, Geology, 1849.
[3] Dutton, C. E., Hawaiian Volcanoes: U. S. Geol. Survey, Fourth Ann. Rept., pp. 75-219, 1884.
[4] Hitchcock, C. H., Geology of Oahu: Geol. Soc. Amer. Bull., vol. 11, pp. 15-57, 1900.
[5] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey, Prof. Paper 88, 1915.

ranges (figs. 3 and 4). These are most prominent in the region north and east of Honolulu and are remnants of the original flow slopes of the Koolau cone. The similar facets on certain parts of the Waianae flanks are less well preserved but are of similar origin. Those on the Koolau Range show essentially the same degree of slope as the underlying basalt

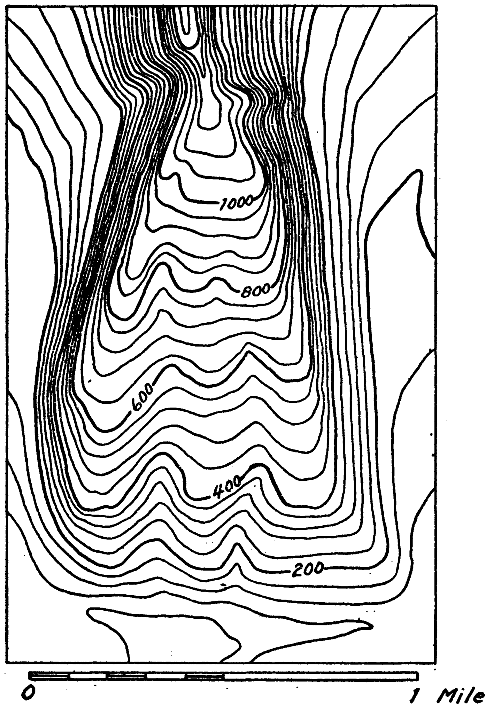

FIGURE 3.—Topographic map of flow slope facet east of Manoa Valley. Redrawn from U. S. Geological Survey topographic map of Oahu.

flows and dip generally directly away from the crest of the range. At the north end of the Koolau Range the dips of these flow slope facets swing sharply around from southwestward to west and thence to north. So much of the east end of the Koolau arc has been eroded away that strong evidence of a pronounced swinging of the dips of the facets is lacking but a similar turning is suggested by such parts as remain.

The conclusion reached by early observers that the arcuate Koolau Range was a remnant of a great circular crater some 25 or 30 miles in diameter, now three-fourths removed either by erosion or faulting, has not been accepted by all geologists. Examination of the configuration of recent and nearly complete volcanic masses—such as the island of Hawaii

as well as that of eroded masses such as the two parts of Oahu, and of the island of Molokai—lead to the conclusion that it is erroneous to assume that all volcanic cones, even those which are simple units, are circular cones and conversely that it is equally erroneous to assume that all roughly circular arcuate remnants are parts of simple circular cones or craters

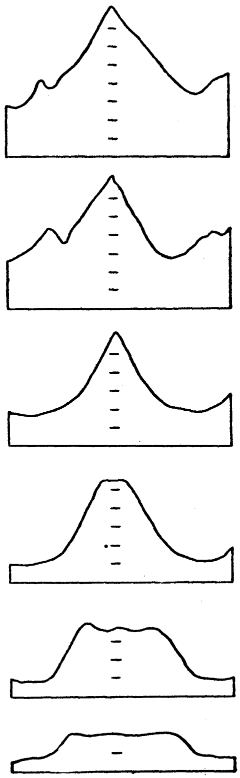

FIGURE 4.—Serial profiles of flow slope facet showing transition inland from broad tabular divide (lower) to narrow knife-edge divide (upper). Scale units are 200 feet.

of the indicated diameter. Especially it seems probable that such a mass as the Koolau Range may be found on detailed examination of its structure and of the remnants of its original surface to have been an elongate cone of ellipsoidal section or perhaps a crescentic cone built around a slightly curved and elongate vent. On this assumption, the amount of the cone which is supposed to be lost is much less; and the magnitude of the necessary faulting or erosion, while considerable, is less appalling than on the assumption of a great circular crater or cone. Rough inspection of the flow slope facets suggests that on either of the assumptions of shape the

center of mass of the conical mass may not have been more than three or four miles, and perhaps even less outside the present land area; and that the existing Koolau Range is to be regarded as not much less than half of the original cone. Similar considerations may apply to the Waianae Mountains, though they are so much more extensively dissected that it is impossible with cursory examination to find any evidence for or against this suggestion.

PRINCIPAL TOPOGRAPHIC FEATURES OF OAHU

The north and east flanks of the Waianae Mountains consist of maturely dissected slopes which at elevations of 200 to 1200 feet merge downward with the smooth and only slightly dissected sloping plain which extends over the interrange saddle from Pearl Harbor to Waialua. West of Pearl Harbor the line between these features has an elevation of about 200 feet, west of Schofield Barracks the plain and its margin against the Waianae Mountains stand at 1200 feet. From a point southwest of Puuiki westward to Kaena the margin of the Waianae range slope consists of a somewhat accentuated and aligned east-west declivity, which appears to be an old sea cliff cut at the time when the Waianae cone was exposed to the sea from the northeast and which was not, like the most of the similar cliff to the eastward, buried under the advancing flows of the Koolau basalts. Inside the curve of the Waianae range are a number of broad, flat-bottomed, blunt-ended depressions separated by web-like projecting ridges. The two broader of these depressions are without well-defined stream courses and do not resemble, except in their general steepness of side slopes, any of the stream valleys of the region. It has been suggested that the physiographic features of the west slope of the Waianae range date from a period when exposure to the trade winds insured more rainfall than is received by this slope at present, but it appears that some additional factors are needed to explain the shapes of these depressions and their relation to the adjacent ridges. Attempts to account for the clean-cut broad bottom flats as a result of marine abrasion at a higher stand of the sea are met by the objection that the spurs are neither terraced on the sides nor truncated at the ends except to a slight extent along the line of the present coast. It appears possible that the depressions may have been cut by streams working in conjunction with other agents at a time when the land stood higher than now and that the flat bottoms of the depression are due to extensive aggradation, but this suggestion has not as yet been tested in the field.

The physiographic features of the Koolau Range are more clearly related to the form of the cone than are those of the Waianae Mountains.

The south and west slopes of the Koolau Range have been deeply dissected by a large number of radial streams consequent on the original lava slopes, and for the most part retaining their original courses. Making the count at about the mid-slope, no less than sixty such streams and resulting valleys are found along the Koolau flanks from Makapuu Head to Waimea. The valleys are characterized by the general straightness of their courses, by their general lack of tributaries, by the U-shaped cross profiles common in Hawaii and by the steepness of their upper side slopes and cirque-like head walls. It is proposed to discuss at length in another paper the factors involved in the development of this type of topography and it will suffice here to name these factors as the great porosity of the rocks, the dominance of chemical over physical agencies of weathering, the close relation between rainfall and elevation, and the lack of freezing temperatures.[6]

Between these numerous radial valleys are long, narrow spurs, the upper portions of whose crests are commonly of knife-edge sharpness, whereas the lower ends consist of the triangular flow slope facets (p. 8). The lower ends of these facets are broader because the radial streams are more widely spaced in the peripheral parts of the cone and because the adjacent valleys cut in the lower slopes do not meet. Cutting by shorter streams between the lower portions of the main streams is negligible because the smaller rainfall of the lower slopes is usually insufficient even to initiate such streams. The increasing depth of the valleys toward their source and the closer spacing due to convergence lead to the meeting of the steep slopes of adjacent valleys at a point part way up the crest of each of the intervalley spurs. This is the upper limit or apex of the triangular flow slope facet, which here gives way to the knife-edge crest of the spur. Not all the spurs are developed in this ideal fashion. But a large number of spurs show these features very regularly developed and on nearly all of them the limit between the facet and knife-edge portion may be identified. Observations on Oahu and also on Molokai show that if the slope of the flow slope facet is projected upward over the knife-edge crest that the higher points of the main ranges have been very slightly reduced from their original elevations, and that the most intense destruction of the spurs has been at points intermediate between the facet apex and the junction of the spur with the main range crest.

The lower ends of the spurs from Pearl Harbor eastward to Makapuu Head are truncated by slopes steeper than those of the original lava surface, which meet the slopes at elevations ranging around 200 feet. These truncating slopes stand in similar positions on adjacent spurs, and it is

[6] Wentworth, C. K., Principles of Erosion in Hawaii (abstract): Geol. Soc. Am. Bull., vol. 37, 1926.

clear from this alignment and from the gravel deposits found in some places at their bases, that they are parts of an old sea cliff extending from Makapuu Head to Pearl Harbor which antedates the shore features now extending seaward from it.

Spurs of the typical sort characterize the north end of the existing Koolau Range and extend as far east as Kahuku Point. Southeastward from Kahuku the facets are less and less discernible and soon disappear altogether. From the village of Kahuku southeastward to Kualoa Point along nearly the whole northerly half of the northeast flank of the Koolau Range, the topography is of the maturely dissected sort found on the corresponding slope of the Waianae Mountains. The valley axes are generally turned somewhat to the northward, or left of the direct course normal to the main direction of the range and in this characteristic are similar to the valleys which head opposite them and flow to the westward. The northeast flowing streams of the Koolau slope have more tributaries than those on the other side due to the greater rainfall on the windward side.

From Kualoa Point southeastward to Makapuu Head the windward slope of the Koolau Range takes on a different character. The valleys are much shorter and the spurs between the valleys are more extensively reduced. Viewed in a general way, the slope is a continuous precipice or "pali" as it is called in the Hawaiian tongue. The lower part of this declivity is buttressed by spurs but above the level of 400 to 1000 feet and extending to the full height of the range the face of the cliff has continuous vertical slopes of from 60 to 80 degrees and a somewhat irregular but roughly northwest-southeast direction. The most conspicuous feature of the pali is the presence of enormous canoe shaped channels extending down its very steep slopes from top to bottom. These differ from rill channels in that they are of the same slope as the rest of the pali, are cut no deeper in the lower than in the upper portion, and are cut as broad curves rather than as narrow grooves. In some places the pali face is essentially made up of these nearly vertical flutings.

Seaward from the pali the spurs extend on the average about three miles to the coast. This slope is broken by the elevations of the Mokapu Peninsula and Puu Olomana and Puuloa, which combine to produce the most pronounced shore irregularity of the entire island. There has been much speculation as to the origin of the pali which forms the windward slope of this part of the Koolau Range. Some have attributed it to faulting, others have concluded that it is the result of erosion, in part marine and in part sub-aerial. It seems pertinent to point out that there are two rather distinct motives in seeking to explain this pali. One is the desire to account

for the apparent loss of a large part of the Koolau cone; the other is to account for the impressive declivity of the pali as a topographic feature. It is not possible as yet to give a final answer to the question, but it seems logical to assume that both faulting and marine abrasion are involved in destruction of the Koolau cone. Moreover no great weight need be given to the hypothesis of faulting, for precipitous pali slopes of comparable magnitudes, and undoubtedly of erosive origin, are normal features of Hawaiian topography.

It is clear that extensive faulting has occurred at many places in Hawaii and that some straight and very precipitous coasts are due to this process. This faulting is all of the normal type and produced by the slumping away of marginal parts of the volcanic masses along the line of declivity between the land and sea. It is improbable that such faulting is of deep-seated origin or connected in any fundamental way with the main trend line of the Hawaiian chain.

In the interpretation of such notable declivities as the windward pali of Oahu, it should be borne in mind that though the magnitude of these supposed works of erosion may be such as to stagger the imagination, yet it is incumbent on the advocate of faulting to form some sort of mental picture of the diastrophic events involved, and that lacking positive evidence of faulting this explanation offers no satisfactory escape from the dilemma.

Between the Waianae Mountains and the Koolau Range lies a sloping plain which is believed to be underlain by flows from the Koolau center. The surface of this plain has been altered by extensive aggradation and its surface cut by a few deep gulches, some of which drain northward to the sea and others southward to Pearl Harbor.

In concluding the description of the general topographic features of Oahu, the shore characteristics may be considered. From Makapuu Head westward for about ten miles, the truncated Koolau Range spurs are bordered by narrow coastal flats of a few hundred feet in width, except where the Koko peninsula extends seaward for about two miles in a southwest direction from a point about two miles west of Makapuu Head. On this peninsula are Koko Crater and Koko Head, pyroclastic cones of 1,205 and 644 feet elevation respectively. (See pp. 76-80.) Diamond Head and Kupikipikio Point are about eleven miles west of Makapuu Head and extend the shore line some two miles seaward of the margin of the Koolau Range. Between Diamond Head and the Koolau Range, Kaimuki crater occupies and increases the elevation of a low saddle.

From Diamond Head northwest to Fort Shafter the coastal flat composed of interbedded coral reef rocks, alluvium, and tuff maintains an

average width of rather less than two miles. The tuff crater of Punchbowl, a half mile in diameter and about 500 feet high, is situated near the business center of the city of Honolulu, its inner margin just touching the border of the Koolau Range spurs. Farther eastward the ash cones of Roundtop, Sugarloaf, and Tantalus rise from the lower slopes of the range.

West of Fort Shafter the coastal plain becomes wider, a roughly circular area about three and a half miles in diameter having been built seaward of the range largely by the tuff deposits of the Salt Lake group of craters. Pearl Harbor is an extensive land-locked body of water of palmate form with an entrance about 2,000 feet wide and covering a gross area of about four by five miles. Its several branches are cut off landward along a curve which is tangent at its eastward end with the line of truncated Koolau spurs, and at its westward end with a similar but less well defined margin of the Waianae Mountains. Deeper parts of Pearl Harbor measure more than 100 feet, but the greater part of its area is less than 50 feet deep. On first inspection, Pearl Harbor might be interpreted as a drowned drainage system. It seems more probable, however, that the strongly constricted character with the entire area confluent through a single mouth is a result of the filling of former valleys lying east of the present entrance to the harbor with volcanic tuff from the Salt Lake craters. There seems to be little doubt that the line starting with the truncated spurs of the Koolau Range, swinging westward round the branches of Pearl Harbor, and continuing in the margin of the higher land of the Waianae Mountains is an old shore line, partly erosional and partly depositional, formed prior to the earliest of the pyroclastic eruptions.

West of Pearl Harbor, the flat known as the Ewa Coral Plain continues with a width of about three miles to Brown's Camp. From this point northwest to Kaena Point, the coast consists of alternating beaches and shorter cliff reaches corresponding to the depressions and spurs of the southwest flank of the Waianae Mountains. From Kaena to Kahuku Point, the coast is low and sandy but with no extensive coastal flat. In both directions from Waimea, a cliff rises a few hundred yards back from the present coast, apparently cut when the land stood slightly lower than at present. The northeast or windward coast of Oahu is largely made up of sand beaches bordered by narrow flats a few feet to half a mile wide. A few wave-cut cliffs appear where spurs extend to the coast. The seaward portion of Mokapu Peninsula is composed of the pyroclastic craters, Ulupau Head and Puu Hawaiiloa. Manana Island, north of Makapuu Head, is also a tuff crater. (See p. 80.)

PHYSIOGRAPHY AND STRUCTURE OF CRATERS

GENERAL FEATURES

DISTRIBUTION OF PYROCLASTIC ROCKS

Nearly all the known pyroclastic rocks of Oahu which may be regarded as belonging to the secondary volcanic series lie southeast of a line drawn from Waikane to Barbers Point. (See fig. 5.) If late pyroclastics exist northwest of this line, they must be of minor importance and have no distinctive topographic expression. [Kaau Crater in Palolo Valley and a small ash crater on the slope of Olomana might have been included.—Editor.] These rocks were dispersed from a number of centers. They differ greatly in age, but the time difference between the youngest and the oldest is probably very small compared to that between the eruption of the oldest and the close of the main volcanic activity which produced the Koolau Range.

The separate volcanic centers concerned in all the known late volcanism number approximately twenty and the number of separate volcanic events or local episodes is more than thirty, some of the vents having been active more than once. The separate vents, some of which are well formed craters and other dikes, make up a number of natural groups, the vents of each group having been active very nearly simultaneously as compared to the rather great differences in the times of activity of different groups. These groups are:

- Diamond Head craters and dikes
  - Diamond Head crater
  - Kaimuki crater
  - Mauumae crater
  - Kupikipikio dike
- Punchbowl crater
- Salt Lake craters
  - Salt Lake crater
  - Aliamanu crater
  - Makalapa crater
- Tantalus craters
  - Tantalus crater
  - Sugarloaf crater
  - Roundtop crater
  - Rocky Hill crater
- Koko craters and dikes
  - Koko Head craters
  - Hanauma Bay crater
  - Koko dike
  - Koko Crater
  - Kalama crater
  - Manana crater
  - Manana dike
- Ulupau craters
  - Ulupau crater
  - Hawaiiloa crater

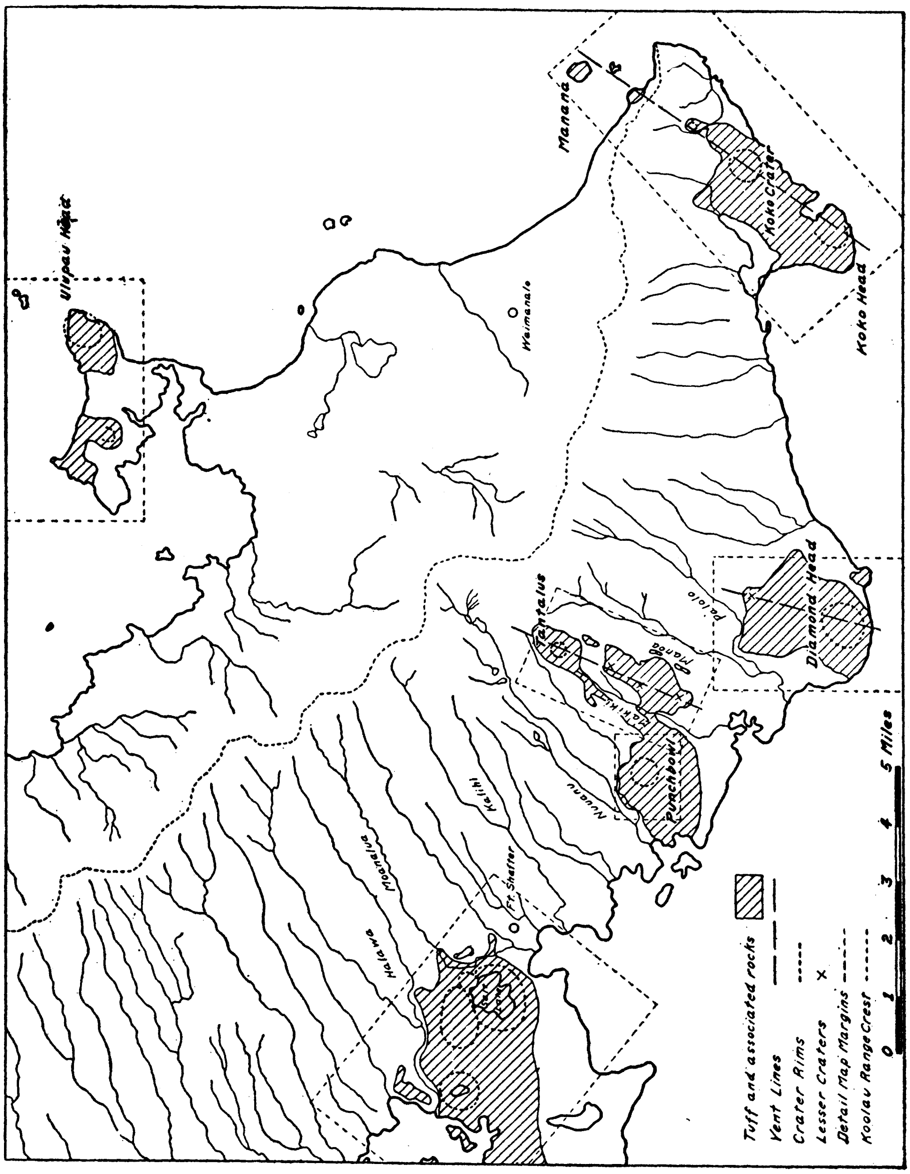

FIGURE 5.—Outline map of southeast Oahu showing drainage and location of the detailed geology maps, figures 15, 18, 20, 21, 22, 24.

Though there is little doubt that very fine grained pyroclastic materials drifted for many miles at the periods of activity, identifiable deposits of tuff are restricted to areas within a radius of about five miles of the vents from which they came. In fact no ash or tuff from one group of craters has been identified with certainty in the territory of another group.

Two difficulties stand in the way of making long distance or minute identifications of volcanic ash on Oahu. In the first place, there are few quiet undisturbed sites of deposition other than the offshore ocean bottom which is still unexposed. In most places the land area is either being actively eroded or is covered with poorly assorted and ephemeral deposits of alluvial and colluvial materials. Only the more massive deposits of ash close to vents are likely to be preserved intact in association with such sediments. The other difficulty which confronts the geologist is the fact that essentially all the rocks in this region are basic volcanics, in consequence of which many of the features of basaltic tuffs are shared by other igneous rocks and their detrital derivatives. Were a basaltic ash wind-drifted even in small quantities over most parts, for example, of North America, its presence could be discovered by the identification of its characteristic mineral and glass fragments. But on Oahu minerals, such as olivine, which occur abundantly in the tuff are equally characteristic of the flow lavas, the bombs, and the ejected blocks of agglomerates, and except for the abundant organic calcareous sand constitute the normal minerals of the derived sediments. Furthermore, as the chemical composition of the tuff does not differ greatly from that of the basalts, the products of prolonged weathering of the two are essentially identical. Therefore only the tuffs with characteristic structures preserved in the thicker and least altered deposits are susceptible of certain recognition.

In most of the pyroclastic eruptions on Oahu the materials have been deposited disproportionately on the southwest side of the vent, as a result of the strength and constancy of the trade winds. This effect is shown in the greater distance of drift to the southwest, its greater thickness on that side, and in the greater height of the immediate southwest rim of the crater. Though there are large individual differences, there is a rough general relationship between distance from the vent and the thickness of the tuff resultant from any one eruption. The maximum thickness of tuff in the leeward or southwest rim of some craters is a thousand feet at distances of about one-half mile from the vent. This thickness decreases very rapidly and at a distance of a mile is rarely over two hundred feet, and commonly less than a hundred. At two miles from the vent, thicknesses of tuff are commonly less than ten feet even on the leeward side.

The distance to which pyroclastic materials have been thrown varies also with the size of the constituent pieces. As is well known from various modern eruptions, fine volcanic dust may be drifted from the vent to the most remote parts of the earth if the general circulation of the upper atmosphere is favorable. In a violent eruption a considerable amount of fine dust reaches the upper atmosphere and remains there for long periods while it is carried to great distances in directions by no means always in accord with the prevailing winds. This process of transportation of volcanic ash may appropriately be designated as dispersal or atmospheric dispersal.

In the Oahu pyroclastics, bombs and blocks a decimeter or more in diameter are limited to distances of a mile from the vent, and most of those a meter or more in diameter found within 600 yards. Correlation of distance with size is very rough and applies only to maximum distance at which a given size appears and not to the proportions of sizes of the fragments at various distances within these limits.

Arrangement of Vents

Somewhat more than half of the craters of southeast Oahu are arranged in three linear groups, those dominated by the craters Tantalus, Diamond Head, and Koko Crater. The Tantalus group includes Tantalus, Sugarloaf, Roundtop, and Rocky Hill. No one of its four craters is more than one-tenth mile distant from a straight line extending about three miles S 20° W from the northern peak of Tantalus. (See fig. 5.) Comprising the Diamond Head group is the main Diamond Head vent, Kaimuki crater, and Mauumae crater. The most probable sites of these vents lie almost precisely on a line trending S 14° W from Mauumae. The most remarkable of the crater lines, that of the Koko group, extends for a distance of about six miles in a direction S 35° W through the Koko Crater vent and from Manana Island to Koko Head. It includes no less than fourteen separate vents and dikes, of which most are distant from a straight line but a few yards. The Manana Island vent is distant perhaps two thousand feet from the line through the other vents but is clearly a part of the same series and the deviation is but trifling from the allineation indicated in figure 5.

It is noteworthy that the three lines of craters described above have trends averaging about S 25° W and are thus not far from right angles to the main trend of the Hawaiian chain. None of the tectonic lines shown by Powers [7] are even approximately parallel to the trends of the crater groups

[7] Powers, S., Tectonic lines in the Hawaiian islands: Geol. Soc. Am. Bull., vol. 28, pp. 501-514, 1917.

of Oahu. Two lines of parasitic cones were observed on the long west slope of the main cone of East Molokai which trend S 18° E and S 56° E respectively. The directions of these do not coincide exactly, but have a rough correspondence with the trends S 36° E and S 65° E of the lines connecting the summits of west Molokai, Lanai, and west Maui as shown on Power's map. In the light of present knowledge it is not possible to correlate the transverse lines of the secondary craters of Oahu with any notable nearby feature, but their close parallelism and exceptional straightness may yet prove to have some significance in the tectonic and volcanic history of Hawaii.

Types of Material

The pyroclastic and other materials making up the secondary craters of Oahu are chiefly tuff, black ash, and basalt. (For descriptions see pp. 91-111.) It is probable that more than 90 per cent of the combined mass of the craters is tuff and that the volume of the basalt extruded is less than 1/100 of 1 per cent of the whole volume of secondary materials. The black ash consists of twisted and pulled droplets of basaltic glass. It varies in coarseness from fine sand to fragments 8 to 10 mm. in diameter. In general it is fairly well sorted, the bulk of any sample being in two or three grades of the 1, 2, 4 mm. scale. The glass pellets are commonly highly vesicular, the vesicles elongate in the direction of elongation of the once plastic pellet. Much magnetite in the form of irregular grains and small octahedra and considerable euhedral olivine is commonly included. Most of the black ash is uncemented but some is indurated to a rather compact rock. In a few places the ash consists of rudely spherical lapilli of basalt which in some layers reach 10 cm. in average diameter. There is no sharp difference between the fine and the coarse ash; the larger masses apparently cooled so slowly as to form basalt rather than glass.

The tuff which makes up the greater part of the craters is typically tan buff or reddish buff in color and is a porous, light, blocky material of moderate to low crushing strength. It consists largely of palagonite, an alteration product of basaltic glass. The tuff now preponderant in the craters has been produced by the alteration of the black ash deposited at the time of eruption. Like the ash, the tuff varies from fine grain to material having the texture of a conglomerate. In a few places it is largely made up of fragments of basalt several centimeters in diameter cemented in a matrix of palagonite but for the most part the palagonite is dominant. Large blocks of basalt ranging to several tons in weight are found in the tuff but are abundant at only a few places, notably the Salt Lake Crater rim. Very few of these masses of basalt show any indication of a liquid or

plastic condition when thrown out. They may well be regarded as parts of the wall rock in the throat of the vent. Huge masses and small fragments of detrital limestone and of coral reef rock are found in these parts of the tuff which have been formed by a subaqueous eruption.

The tuff of the Salt Lake Crater region is in general of grayish color rather than buff and contains considerably more basalt and less palagonite than that of most of the other craters. Most of the tuff of all the craters is deeply weathered and traversed by incipient jointing so that it is pracically impossible to obtain sound symmetrical hand specimen from it.

The basalt of dikes and tiny flows associated with the tuff is mainly slightly vesicular, in places porphyritic, and does not differ materially from the lavas common to Oahu. (See p. 91.)

Form

The secondary craters of Oahu consist typically of a rudely circular rim with relatively narrow crest from which the surface slopes away steeply both inside and outside. (See figs. 6, 7.) The slopes become progressively less away from the rim, the inner slopes merging to a saucer-shaped depression and the outer slopes commonly merging with the pre-existing topography a few hundred yards from the rim. The crater rims range from less than a quarter mile to somewhat more than a mile in diameter. A few like Diamond Head (Pl. 11) and Punchbowl are notably symmetrical both in the circular plan of the rim and in the regularity of inner and outer slopes. Nearly all show the effect of trade wind drift in the higher parts of the southwest rim and some, like Koko Crater, show pronounced asymmetry due to this cause. The steepest crater slopes due to accumulation are those adjacent to the rim crest. These have angles of 35 degrees on the highest craters. Some of the smaller craters are the result of less pronounced or less concentrated accumulation in which the angle of rest of 35 degrees has not been reached.

The more important craters of each group reach a height of 500 to 600 feet, the highest of all, the magnificent leeward peak of the asymmetrical Koko Crater standing 1,205 feet above sea level (Pl. 1). The greater part of this elevation is due to the accumulation of ash during a single eruption.

Weathering and erosion have modified the form of most of the craters to a considerable extent. The channels of ephemeral streams cut along consequent courses down both the inner and outer slopes have depths of 50 to 100 feet in their middle courses. The radial spurs between the channels consist of dip slopes of the tuff and by weathering are being stripped of layer after layer. The heads of the channel valleys are steep funnel-

shaped alcoves or triangular pali facets between the buttressing spurs. The lower slopes of the crater both inside and out are commonly aggraded to varying depths with more or less cemented talus breccia derived from the upper slopes. The inner slopes of the craters merge with a low aggraded central flat which has been formed by alluvial filling, which quite obscures the original features of the vent.

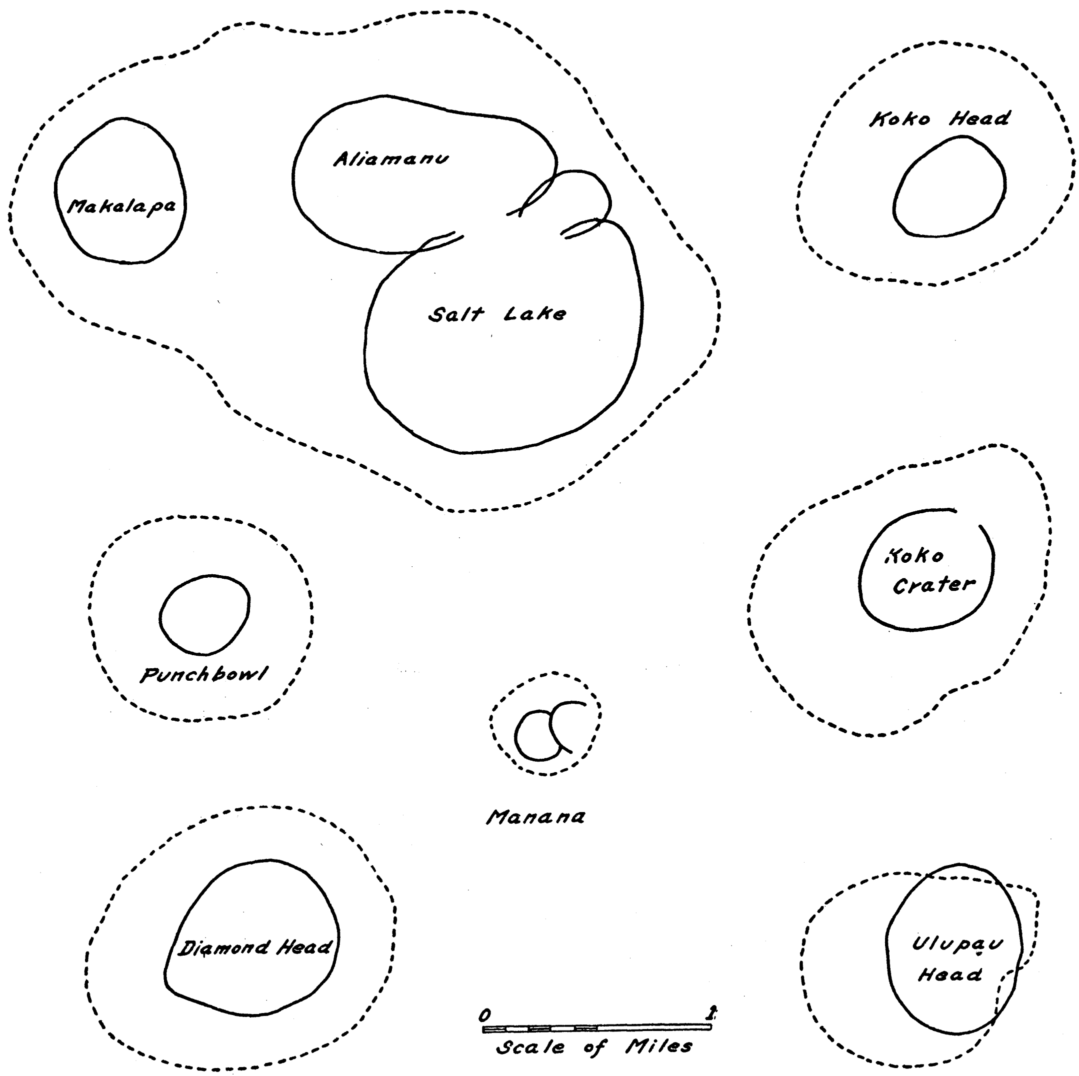

FIGURE 6.—Composite diagram showing relative sizes and horizontal forms of the rims of the principal secondary craters of Oahu. Rim crests in solid line; approximate present limits of tuff formations in dotted line.

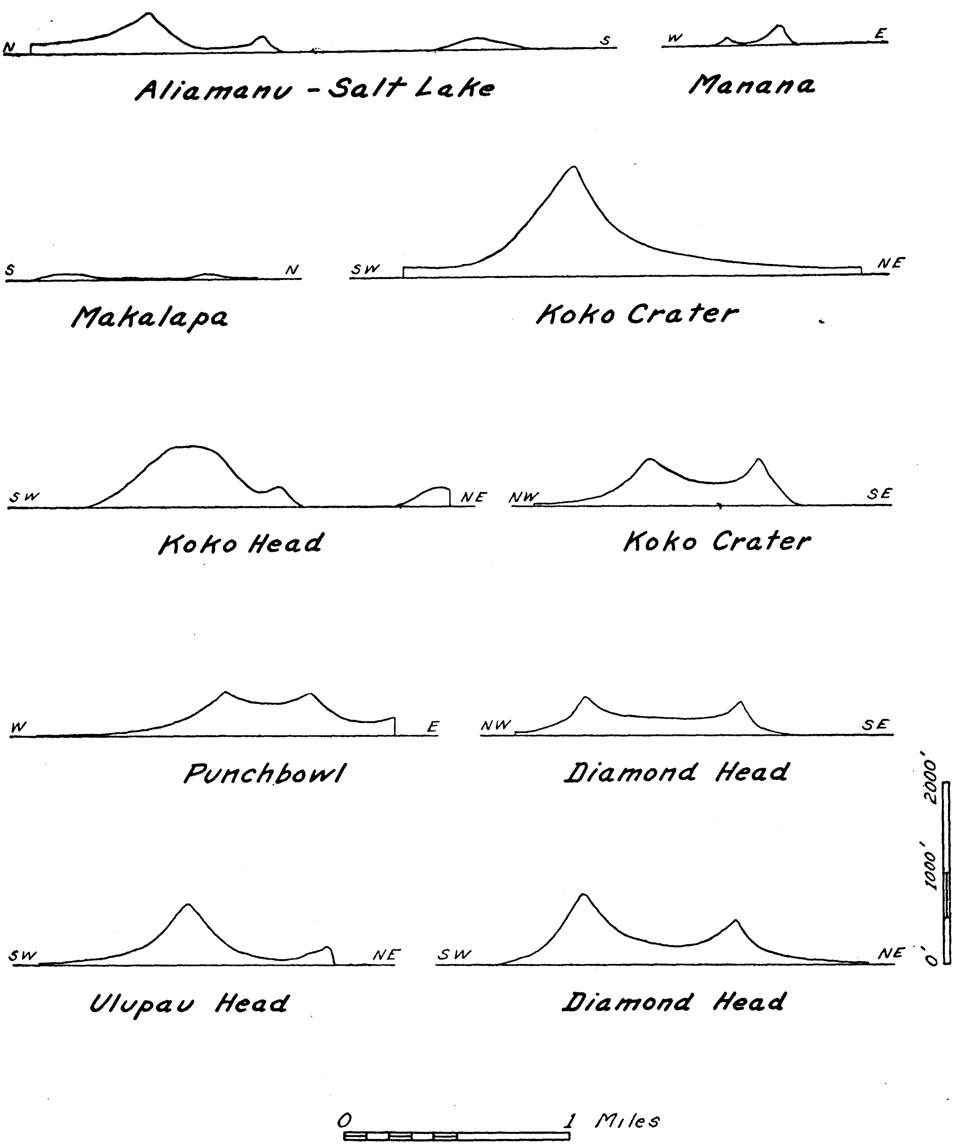

FIGURE 7.—Composite diagram showing the profiles of the principal tuff craters of Oahu. Vertical scale approximately twice the horizontal.

Gross Structures

The essential structure of the craters is simple. (See fig. 8.) The dips of the beds are toward the center inside the rim and away from the center outside the rim. They are greatest a few tens or a few hundreds of feet outside and inside the crest of the rim and downward and away from these zones become progressively less. Between the steepest outward and inward dips is a broad curve 50 to 200 feet across, the beds being horizontal at the original crest (Pl. III, *B*). The deeper beds beneath the rim have much gentler dips and it is apparent that the angle of rest which fixes the

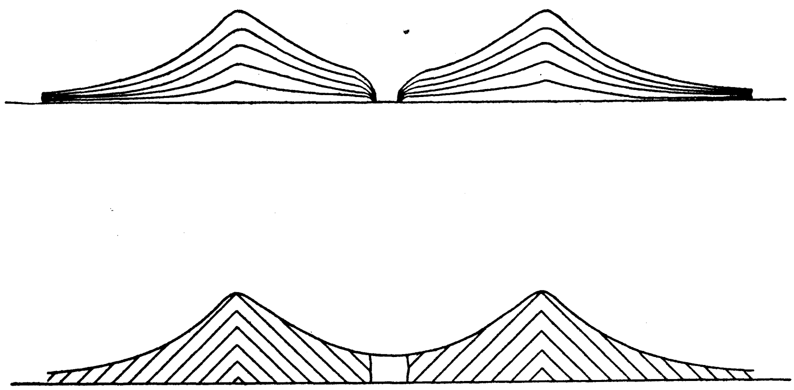

Figure 8.—Ideal diagrams showing correct and incorrect interpretations of structure of pyroclastic craters. (*a*) Actual structure with high angles of dip only in the upper parts of the mass and a curved transition at the crest. (*b*) Structure as represented by some writers.

maximum of in-dips and out-dips at approximately 35 degrees is only reached after the rim has been built up to considerable height by accumulation of material. The rounded transitional curve between the maximum in-dips and out-dips is the result of the fact that the greatest accumulation is not precisely on a circular line but is a less definite circular zone of appreciable width. Indeed, when careful consideration is given to the conditions of origin of these craters it is surprising that the rims are so nearly sharp-crested. Their structure indicates a remarkable constancy of range of projection for the bulk of the material during eruption. Attention is called to the rounded structural crest, to the progressive diminution of dips away from the rim, and to the lesser angles in the lower parts, since previous descriptions of some of these craters show crests of knife-edge sharpness, and dips about 45 degrees throughout and indicate that the crater retained a sharp rim crest from its very inception.

It has been stated that the dips at the structural crest of the crater are horizontal. This is true in so far as the radial section is concerned. For a considerable part of the rim the beds are essentially horizontal both radially and tangentially. In most of the craters there has been excessive building up of the southwest part of the rim. After this part of the rim has reached an elevation greater than adjacent parts, the process of mantling produces a structure which not only dips away from its rounded crest inward and outward, but also, considered as an anticline, plunges tangentially along the rim away from the highest point. Thus dips in the vicinity of the high southwest point are likely to deviate from a direction radial to the vent toward a direction radial to the highest point of the rim, and the actual dip is the result of a combination of these tendencies. High points on some craters are developed at parts of the rim other than at the southwest, and through other causes. For example, it seems likely that with a slight shift in wind direction or change in conditions of eruption, the position of the circular zone of maximum accumulation might be shifted in such fashion as to be partly inside and partly outside its former position. If this took place, the points at which the new zone crossed the old zone would be upbuilt excessively and become the centers of plunging anticlinal dips. A very slight shifting of this sort would be needed to produce a considerable deviation of dips from the strict in and out and rounded crest condition. There are other variations in the structures of individual craters from the ideal types, some of which are clearly due to the configuration of the old topography and others whose origin is not apparent. In the areas surrounding the craters where the tuff or ash is but a few feet or a few tens of feet thick, synclinal dips are common where old valleys have been mantled and monoclinal dips are found in various places where cliffs such as those along the sea have been covered. Reports of previous observers of folding and other deformation of the tuff seem to be based largely on the original structures due to mantling, and reliable evidence of deformation other than the most obvious surface slumping is lacking.

Bedding of Pyroclastic Rocks

The undulatory but continuous type of bedding of the pyroclastics has been designated a "mantle bedding." Its features are due to the process of settling from an essentially static fluid—a process which determines the shape, continuity, and texture of the beds. The chief characteristic of mantle bedding is a very gradual textural transition. For example, a bed of tuff several inches thick and containing no lapilli over 2 mm. in diameter may grade upward within a fraction of an inch, but not abruptly, to an

agglomeratic tuff with fragments of basalt or of reef rock 10 to 15 mm. in diameter. In many aqueous formations successive beds are the result of the deposition of materials over a surface having a sharp and completed upper limit. In pyroclasts the changes in the beds are due to slow changes in the composition of the aerial mixture. The deposition of coarser materials takes place in zones and thin lines as episodes during a more continuous deposition of the finer ejectamenta. From the standpoint of composition and genesis, the type of bedding produced is not unlike that of a limestone which contains in some zones considerable quantities of accessory clastic materials without change in the general character of the calcareous matrix (Pl. III, *C*).

In type of bedding the so-called black ash (p. 95) differs from the tuff. Its individual beds are more sharply defined, are more uniform in thickness, and composed of more uniform material. But there probably is no fundamental difference between the bedding of the tuff and of the ash, the two kinds of materials grading imperceptibly into one another. It seems likely that the beds of ash which consist of the better sorted material and thus were more porous have been affected less by the action of ground water in producing cementation and alteration of the basaltic glass to palagonite, and therefore have been unchanged from the unconsolidated ash condition. Thus, better sorting, with less very fine material, higher porosity, and more uniform bedding characterize those strata which are still in the condition of black ash of various grades of coarseness.

Most of the bedding surfaces are plane over limited areas but subject to rather rapid curving and change of direction of dip where irregular surfaces have been mantled. On a few bedding surfaces are markings which closely resemble ripple marks. All of them are nearly parallel with strike of the beds and it seems not improbable that they are ripple marks of eolian origin formed during a slight cessation of deposition.

In the mantle type of bedding it is difficult to determine the thickness of beds, for different observers disagree as to what constitutes a bed. In general the beds are thin; in a hand specimen 3 to 4 cm. thick several zones may be distinguished. In the face of a large outcrop, alternations from coarse to fine material take place in zones of a meter or two in thickness and within these zones, especially those of finer texture, is a graded series of zones of various orders of magnitude.

It is natural that a ten-foot zone of variable coarse material seems more homogeneous than a ten-foot zone of variable fine material for the reason that the smaller units of the fine material permit more variations. But the difference is more apparent than real and is due merely to choice

of an absolute unit of ten feet of thickness rather than a unit based on degrees of coarseness.

Minor Structures

The most common minor structures in the tuff are the prominent depressions of the layers which occur where bombs and blocks have landed. These will be designated as bomb sags. The beds opposite the center of the bomb are affected most, but beds down to a point below the bases of the bomb are depressed, and the beds immediately over the bomb show a slightly mounded structure. (See fig. 9.) In section, the bomb sags vary from a concavity of moderate depth to deep sack-like depressions in which the

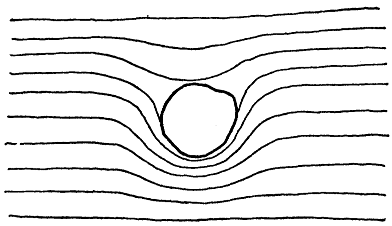

Figure 9.—Sketch of bomb sag showing deformation of bedding.

depth is greater than the width. Where three-fourths or more of the bomb is exposed by weathering, the indipping bedding surrounding the bomb is commonly weathered out differentially to a series of concentric ridges. The popular assumption that these concentric rings are wrinkles formed when the bomb landed in a soft mud is quite untenable. Theoretically, it seems possible to deduce the direction from which the bomb came by inspection of the concentric structure, but at no locality visited could this be done with confidence. Probably most of the bombs fell with a final path nearly vertical.

Bomb sags are roughly proportional in size to the bomb or block which formed them and range in diameter from 4 cm. to 3 meters. Differences in depth of the sag are doubtless due to the varying compactness of the ash into which the bombs fell.

Casts of stems and roots of small plants and of trunks of trees are found both in the less cemented black ash and in the palagonite tuff. In the black ash the material surrounding the trunk or stem is usually more thoroughly cemented with a calcareous matrix than is the rest of the ash. Presumably the stem has served as a route for the circulation of ground water and the cementation thus facilitated. The casts are found in both

horizontal and vertical positions, many sufficiently branched to give an impression of the habit of the tree.

Associated with the stem casts are anomalies of bedding which are due to the elevation of the beds adjacent to the tree trunk by the process of mantling. These may be called tree trunk cusps or cuspate bedding. They are not always presented but have been observed in some of the few places where trunk casts are well exposed in vertical section (fig. 10).

The main joints in the tuff, many of which are now filled with calcium carbonate, are developed along lines roughly radial to the craters. There

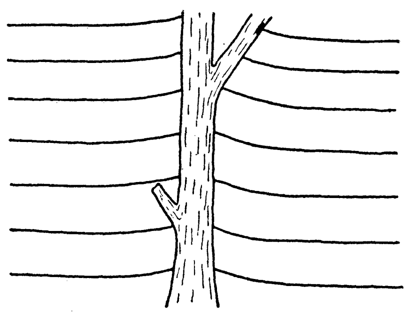

FIGURE 10.—Diagram showing cuspate bedding caused by banking of ash around tree trunk and settling of the newly fallen ash.

are many exceptions to this rule. These joints have exerted considerable control over the consequent stream channels which follow them in places for some rods.

Close spaced systems of parallel fractures making structures resembling schistosity were observed at a few places in the tuff. They appear to be of purely local origin and due to small amounts of shearing. It is hardly to be expected that any real schistosity has developed because of the lack of minerals favoring such alteration.

A minute columnar structure, consisting of columns 3 to 10 cm. thick and 20 cm. long, has been developed at one locality by the heating of surface layers of tuff by an overlying lava flow. (See Pl. IV, *A*.)

WEATHERING AND EROSION

Two weathering processes appear to affect the tuff; for convenience they can be designated as crumbling and subspheroidal spalling. Crumbling goes on nearly everywhere at the surface and the loosening of the grains by gradual decay of the cementing matrix extends downward for a few feet (Pl. IV, *C*). Spalling is apparent at various places where the clean

rock is exposed to the air, though its effect seems to be initiated throughout much of the tuff within 20 to 30 feet of the surface.

The characters of subspheroidal spalling are rather definite and the process leads to fragments of distinctive shape. (See Pl. IV, *B*.) The main difference between this spalling and true spheroidal weathering is that in the spalling the fragments which come off the surface are much thicker in the middle than at the margins and the result is a polyhedral block with curved faces intermediate in convexity between planes and the normal curvature of a spheroid of the same size. Some blocks split easily through the middle and each half spalls down by the removal of corner and edge spalls to an equidimentional polyhedron of a form similar to the original block. Even the larger and thicker double concave lenticular spalls tend to break down to smaller polyhedral nuclei by the same process. The incipient surfaces of parting are so well developed that by pressure of the fingers a chunky block 10 to 12 cm. in diameter may be spalled down successfully to a nucleus about 1 cm. in diameter. After the polyhedral form of one size is departed from by the removal of one spall, several more need to be removed before the shape again approaches a regular polyhedron. The horizontal joints appear to be a little stronger than others and the upper surfaces of some exposed beds are weathered out to remove some of the upper corner spalls from component polyhedral blocks. These blocks, when separated, have the upper end of the prismatic form more rounded than the lower and have a general form similar to small biscuits.

The nature of the process producing the subspheroidal spalling is not well understood. In some respects it resembles spheroidal weathering due to temperature changes, which is a type of exfoliation. It seems unlikely, however, that temperature changes are a major factor in subspheroidal spalling or in the better developed spheroidal weathering common to Hawaiian basalts. No measurements have been made of the temperature of the surface rock or of the air immediately surrounding it, but so far as can be judged from the records of the Weather Bureau, the diurnal changes and other rapid changes in Hawaii are insufficient to produce any appreciable amount of exfoliation. Much of the spheroidal weathering takes place below the surface or in such protected situations as stream valleys and other depressions, where temperature changes are small. No evidence of exfoliation was seen on Oahu in any rock and has not been observed by Gregory [8] in his studies of the higher parts of Mauna Kea.

As an alternative cause for the spheroidal weathering, expansion due

[8] Gregory, H. E., Glaciation of Mauna Kea, paper in preparation.

in part to wetting and in part to chemical weathering favored by the penetration of ground water seems a possibility.[9]

The physiography of the regions peripheral to the tuff craters does not differ materially from that of areas which were not ash mantled. In a few places drainage has been changed after the filling of pre-existing valleys by the ash but most valleys were not so completely filled but as to prevent the streams from reassuming their old courses.

All the valleys which have been developed by intermittent streams on the slopes of the tuff craters are similar and show certain well marked characteristics. The longest measures not more than a half mile from head to mouth; most of them are much shorter. None have permanent streams and all have high gradients and deep, narrow cross-profiles (Pl. V, *A*). The longitudinal profiles of the stream channels are similar to the profiles of the crater slopes except that they are more deeply concave. At their heads the channels are shallow (measured as an indentation normal to the tuff slope) and are steeper in gradient than the tuff slope. In mid-course, the channels are deeper and have for a short distance essentially the same gradient as the tuff surface and as the bedding of the tuff. Lower down, the channels again become shallower and have gradients of somewhat less than the tuff slopes. These slope relations are characteristic of valleys in most parts of the world except that in few places can so clear a view be obtained of the entire length of streams developed on concave slopes of such regularity. The lower parts of the channels throughout their course are cut in fairly fresh tuff and consist of smoothed and rounded walls, which in many places are marked with short parallel striae showing the direction of water passing along the channel. The individual scratches are short and slightly variable in their direction and show clearly their formation by a mobile fluid by the extent to which they are influenced by the harder and softer spots in the rock. Such scratches have been observed at several localities, even on moderately hard rock. They are not likely to be considered by an experienced observer as glacial in origin, although streams as well as glacial ice may striate the rocks over which they pass.

The typical relationship of the channel to the strata of the tuff in different parts of the courses of the streams is worthy of brief description. In the upper part of the course the channel gradient exceeds the dip of the beds. However, instead of following a smooth profile of the required gradient, the bottom of the channel usually consists of short stretches of 10 to 20 feet where the channel follows the low dip of the bedding

[9] Wentworth, C. K., Geology of Lanai, B. P. Bishop Mus. Bull. 24, p. 41, 1925.
Blackwelder, Eliot, Exfoliation as a phase of rock weathering: Journ. Geol. vol. 33, pp. 793-806, 1925.

alternating with steeper sections where the channel cuts down across the beds with a gradient in excess of the dip. Many streams of moderate to high gradient have alternating reaches and rapids in their courses; in the upper parts of these channels the reaches coincide with the bedding and the rapids transgress the bedding. In their middle course, many of the channels follow the dip of the beds nearly continuously for a few hundred feet. In the lower section, the condition is reversed and the rapids follow the dip of the beds, whereas the reaches transgress the bedding to higher and higher strata. In this part of the course the reaches are commonly more or less aggraded with poorly assorted debris. Potholes are a normal and important part of the narrow channels, especially in the upper portion where they are common at the lower ends of the rapid sections. Because of the steep gradient of the channels, which gives the water a forward component of motion, as well as because of the attitude of the beds many of these potholes are deeply undercut on the downstream side; some show a strongly marked spiral form in which the water swirls in one direction, entering from the upstream side, swinging round the undercut downstream side, spiralling upward on the return and passing out over the lip at the completion of the circuit. (See Pl. V, *B*.)

The channels, which are dry except for a few days, or even a few hours, during the year, have considerable debris in their lower courses but contain only freshly loosened blocks of tuff and large fragments of basalt in their upper parts. Most potholes contain a few large blocks or cobbles and some of them are choked with finer debris washed in during waning stages of the last flood. The channels in many places are but a few inches wide at the bottom and not over four to six feet wide at the height of a man's head. Large bombs or blocks weathered from the tuff sometimes lodge in these narrow places and remain as keystones for the lodgment of other materials.

As a result of superposition some channels have a course which does not quite coincide with the direction of steepest dip. These channels tend to "slide" strongly toward the down dip side, stripping the tuff beds as they shift in that direction.

No very well rounded or sorted materials are found in the tuff channels, as is to be expected from their very slight length, but due to the softness of the tuff and probably to its transportation in a bare, pot-holed channel, there is an amount of shaping of the debris not found in the first few hundred yards of the courses of most streams. The washing of materials in potholes has formed concentrates of olivine sand, which, though not as well sorted as those on the beaches, are still striking segregations of crystal sand grains.

ORIGIN

1. All the black ash, agglomerate and palagonitic tuff observed on Oahu was deposited from the air as essentially dry material. Very subordinate parts were subject to contemporaneous reworking by streams or waves and are mingled with the more common kinds of detrital sediments. No tuff is known on the island which gives evidence of ejection as volcanic mud, hot or cold. Both the major and subordinate structural features point overwhelmingly to an aeriform origin and are entirely out of accord with the hypothesis of origin as hot mud, which has been extensively advocated in the past.

2. The pyroclastic rocks are closely associated with and grade into rhyoclastic rocks and minor flows. It appears most natural that this should be so. Without attempting to discuss the vent mechanism of pyroclastic action, it may be stated briefly that pyroclastic rocks result from eruptions in which the expulsive action is violent and the supply of molten material at the vent relatively small. Indeed, it is believed that the relation between these two factors, rather than the absolute violence of the expansive force beneath the crust, largely determines the character of an eruption. The same pressure required to raise a considerable and continuous column of liquid lava to the surface would be quite sufficient to cause violent emission of finely divided pyroclastic materials if the amount of the molten lava available were small and its delivery somewhat discontinuous. Under conditions of this sort, it is apparent that alternations between true pyroclastics, rhyoclastics, and small flows would be the rule rather than the exception, due to fluctuations in the arrival of liquid material at the immediate vent.

3. The present condition of the pyroclastics is due to the greater or less amount of alteration to palagonite and of concurrent cementation. This is controlled in part by the original fineness and perfection of sorting and in part by the situation and depth of burial as influencing aqueous alteration.

DIAMOND HEAD CRATERS

PREVIOUS STUDIES

Diamond Head is the best known of the pyroclastic craters of Oahu and in its various characteristics is the most ideal example of the class. It has been the center of the gradual evolution of views as to the origin of the pyroclastic craters.

The earliest known account of the geology of Diamond Head is by Dana,[10] who visited Oahu in 1841 as Geologist to the U. S. Exploring

[10] Dana, J. D., U. S. Exploring Expedition (Wilkes), vol. 10, Geology, 1849.

Expedition under Captain Charles Wilkes. Dana described the crater as a typical tufa cone having its stratification parallel to the bottom of the saucer-shaped crater and to the original outer slope. He concluded that the brown color of the tuff was evidence that the water in or with which the ash was deposited was at a temperature of less than 200° F. In 1891, following a second visit in 1887, he states [11] that the southern brow has lost some of its boldness by erosion since 1841. Brigham [12] states that the cone of Diamond Head is rapidly being reduced by erosion and that the outward dipping beds have been largely removed on the south and west slopes. At this time (1868) more than half of the bottom of the crater was covered part of each year by a pool of water.

Green,[13] describes the Diamond Head tuff as "a genuine tufa in thin laminae the effect of the junction of sea water and molten lava."

A brief description of Diamond Head was given by Dutton [14] in 1884. Stating that it is composed of cinders and tuff, he made no specific interpretation of its origin. Hitchcock [15] described Diamond Head as an outflow of volcanic mud which continued for a time and then after the supply failed fell back at the center, leaving the existing depression. He quotes the opinion of Brigham that the summit of the southwest rim was 25 feet lower in 1899 than thirty years before. Hitchcock recognized that Diamond Head is older than the Kaimuki and Kupikipikio lavas and considered that the black ash east and southeast of Diamond Head probably came from Kupikipikio.

Bishop [16] refers to Diamond Head in two published papers. Diamond Head was formed by the projection of hot mud "miles aloft." He considered Punchbowl crater to be much older than Diamond Head and calls attention to the great regularity of the crater of Diamond Head, which he considers strong evidence that it was formed in one brief episode of probably less than one-half hour but at most not many hours. Following certain reasonable assumptions regarding the size of the vent he presents computations of the height of the fountain and velocity of discharge. According to Bishop, both Brigham and Green had correctly attributed the greater height of the southwest portion of the rim to the effect of the trade winds on the ejected material. He describes this material as "semi-liquid tuff."

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[11] Dana, J. D., Characteristics of volcanoes, p. 293, 1891.

[12] Brigham, W. T., Volcanic phenomena of the Hawaiian islands: Boston Soc. of Nat. Hist. Mem., vol. 1, pt. 3, p. 360, 1868.

[13] Green, W. L., Vestiges of the molten globe, pt. 2, p. 178, 1887.

[14] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Surv. Fourth Ann. Rept., pp. 217-218, 1884.

[15] Hitchcock, C. H., Geology of Oahu: Geol. Soc. Am. Bull., vol. 2, pp. 43-46, 55-57, 1900.

[16] Bishop, S. E., Geology of Oahu: Hawaiian Annual, p. 13, 1901; Brevity of tuff cone eruptions: Am. Geol., vol. 27, pp. 1-5, 1901.

W. H. Dall[17] reached the conclusion that Diamond Head had been formed slowly in relatively shallow water and had been elevated without being deformed. He considered that the earlier layers were deposited intermittently and that corals and molluscs flourished in the intervening periods. Hitchcock[18] summarizes the views of previous workers with especial attention to the conflicting interpretations of Dall and Bishop and concludes:

1. Diamond Head is a tuff cone thrown up explosively from beneath the level of the ocean and is to be compared with the Monte Nuovo, near Naples.

2. It was ejected through fossiliferous limestones of Tertiary age, probably Pliocene.

TOPOGRAPHIC EXPRESSION

The native name of Diamond Head is Leahi. The name Diamond Head is said to have been applied because sailors found there calcite crystals which they mistook for diamonds. As calcite crystals at Diamond Head are inconspicuous it is probable that the sailors found olivine crystals, good specimens of which are abundant in the beach sands.

Diamond Head lies about one and one-half miles south of the ancient wave-cut margin of the slopes of the Koolau Range. (See figs. 1 and 5.) It forms at the present time a bold promontory extending a mile beyond the general coastline and on its southern and southwestern sides rises steeply from the narrow marginal beach. To the west and east lie low plains for the most part not over 20 to 30 feet above sea level. To the north, Diamond Head is separated by a low gap from the Kaimuki spur which extends about a mile south from the Koolau Range. Immediately northwest of Diamond Head is Waikiki beach and about one mile east is a much smaller promontory known as Kupikipikio Point (Pl. V, *C*). Diamond Head is a familiar sight to travelers who visit the port of Honolulu and because of its circular outline presents from different directions a changing but always characteristic profile.

Diamond Head has the form of an inclosed nearly circular crater and is about two-thirds of a mile in diameter. (See figs. 11, 12, 13.) The principal departure from the circular form is an elongation of the rim in a direction about S 60° W so that this diameter is some 15% greater than the normal diameter. This elongation takes place wholly on the southwest side, and the rim on this side has nearly the form of two tangents which meet in a slightly rounded angle of about 110 degrees. (See fig. 14.) The

[17] Dall, W. H., Notes on tertiary geology of Oahu: Geol. Soc. Am. Bull., vol. II, p. 58, 1900.

[18] Hitchcock, C. H., Geology of Diamond Head: Geol. Soc. Am. Bull., vol. 17, pp. 469-484, 1906. Hawaii and its volcanoes, Honolulu, pp. 33-34, 1909.

rim of the crater has an average altitude of about 410 feet. About one-fourth of the total length of the rim is below 400 feet, slightly over one-

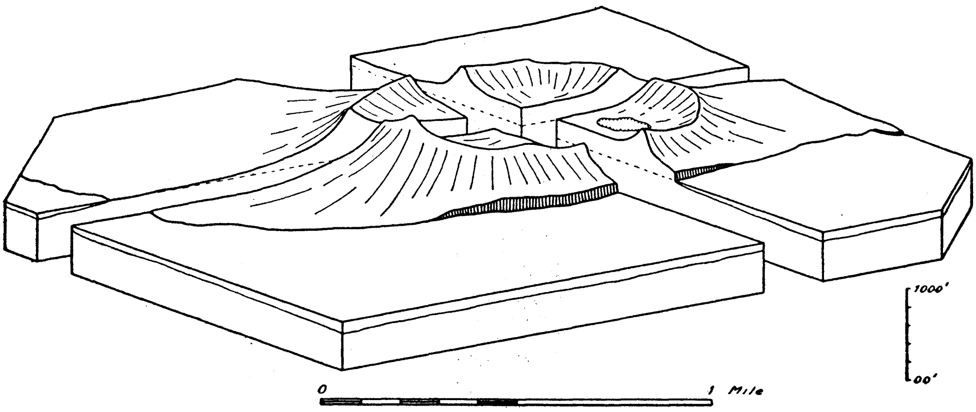


FIGURE 11.—Block diagram of Diamond Head dissected to show profiles in two directions.

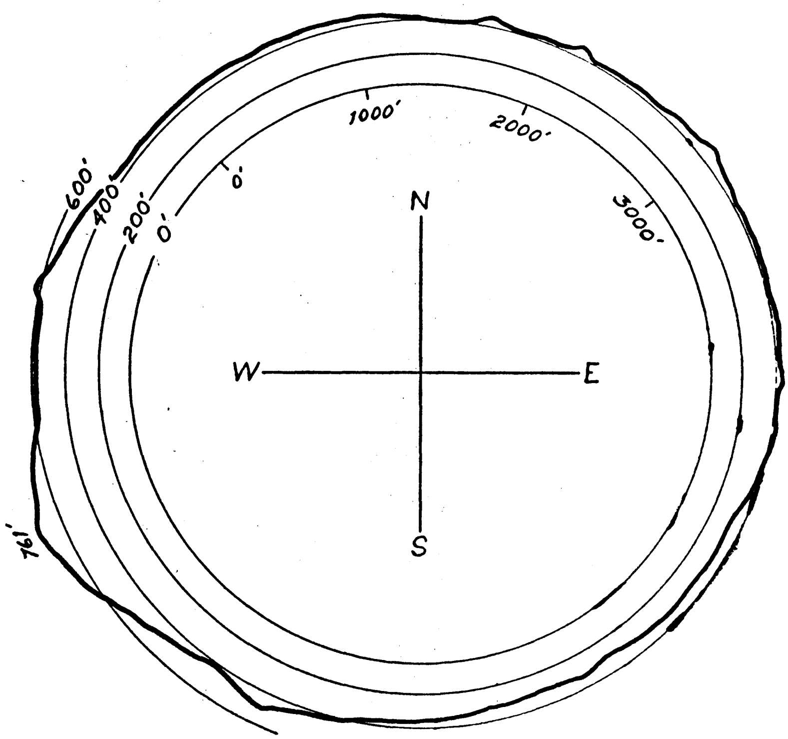


FIGURE 12.—Profile of the Diamond Head rim crest drawn on a circular base showing the high southwest summit and general uniformity of elevation of the remainder of the rim.

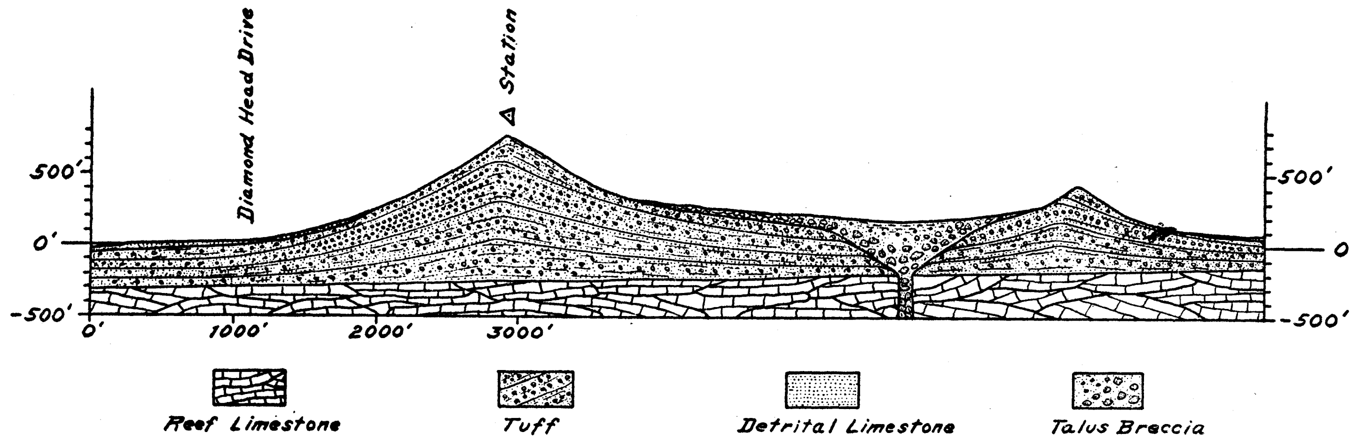


FIGURE 13.—Structure section of Diamond Head in a N.E.-S.W. direction through the summit peak. The structure of the reef limestone and of the filling of the vent is hypothetical. The structure of the main mass of tuff is interpreted on the basis of field observation of Diamond Head and other craters.

half is between 400 and 500 feet, and the remainder is over 500 feet in altitude. The highest point, 761 feet, is at the southwest side, and the lowest point, about 320 feet, is at the southeast, above sea level. (See fig. 12.)

A little over half the area within the crater lies below 300 feet and less than a tenth of this below 200 feet. The lowest point, which is nearly due east of the center of the crater, is but little under 200 feet in elevation. Drainage both inside and out is along radial lines in narrow, steep-sided

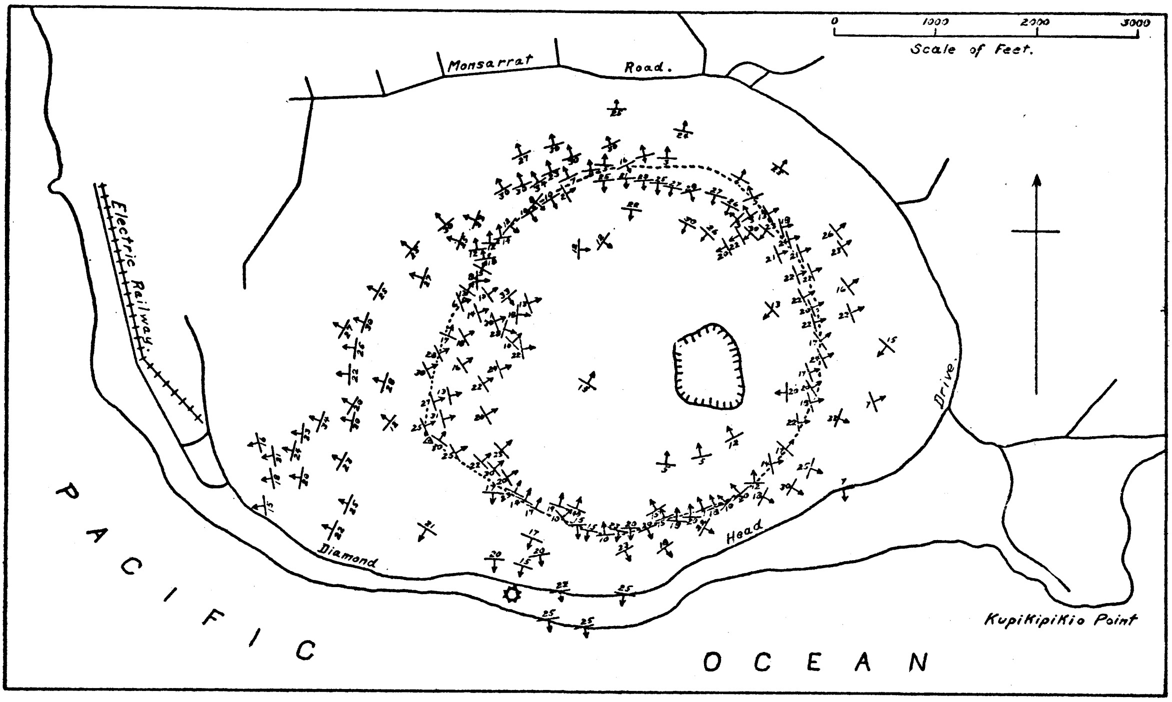


FIGURE 14.—Structure map of Diamond Head showing the typical inner and outer radial dips.

ravines. There are no streams which flow, except for brief periods following heavy rains. The interior drainage runs to the lowest point and there disappears by seepage. Residents of the region who were familiar with the crater prior to its establishment as a military reservation say that during the rainy winter season a pond some two or three hundred yards across occupied the lowest part of the crater bottom for two or three weeks at a time. Army officers report that the lake has appeared several times since 1909, lastly in 1916. It appears that flooding of the lower crater bottom has been less frequent in recent years. This change may be related to a periodic fluctuation of rainfall or a progressive change toward dryer condi-

tions. There is a bare possibility that this change may be in some way connected with the general lowering of the ground water level in the Honolulu region in recent years.

The slopes of Diamond Head are sparsely covered with vegetation where conditions permit the accumulation of soil. The principal tree is the kiawe (algaroba, mesquite). The area inside the crater which has formerly been ponded is clearly indicated by the absence of kiawe trees, as the species has a strongly xerophytic habit.

Two-thirds of the rim of Diamond Head is a sharp crested circular ridge with a width at the base of 500 feet to 800 feet (fig. 12). The slopes in general are steep, the outside slopes being dissected into an alternating series of ravines and spurs. The remaining one-third of the rim, including all those parts of the crest rising above five hundred feet is somewhat less regular, much more massive, and much more deeply dissected. It is the only part of the crater which shows any considerable amount of dissection of the inside rim.

In the Diamond Head mass the ravines are deep, narrow trenches which follow radial courses and are controlled locally by joints which likewise have a general radial arrangement. The ravine bottoms, most of which are but two or three feet wide,—in some places but a few inches,—consist of alternating reaches and rapids cut in the bedrock tuff. Where the gradient of the channel is less than the dip of the tuff, the reaches are developed across the edges of strata and the rapids sweep down a dip slope. Where the gradient of the channel is greater than the dip of the strata, the reaches are developed on the dip slopes and the rapids or falls transgress the edges of the beds. At the foot of the falls potholes are common and in the steeper portions of some ravine channels the chief mode of erosion is by downward and mouthward abrasion of a series of potholes. In the greater portion of the ravine courses transportation is more vigorous than weathering immediately adjacent to the channel, which is swept clean except for a thin veneer of detritus along parts of the reaches and for the coarser material which has lodged in the potholes. The resistance of different beds of the tuff does not vary greatly and the side walls of the channels are generally fairly smooth, except near their tops where weathering has produced somewhat more differentiation of strata. Blocks and bombs of basalt protrude from the walls and floors of the channels until they are more than half exposed and finally loosened by the removal of tuff from around them.

At the heads of most ravines are cliffs of 50 to 200 feet in height. The smaller ravines head in rounded funnel-like coves, above which are graded slopes of spurs. Most of the cliffs at the heads of the larger ravines rise

thence nearly or quite to the crest of the crater rim and range from slopes of 70 degrees to vertical or slightly overhanging declivities. The form of the cliff face is commonly that of a triangle with the apex below and the sides flanked by the more stable material of the adjacent spurs.

Between the ravines are long, narrow radial spurs which have longitudinal slopes averaging 30 to 35 degrees, but in places cut back at the base so as to slope 40 to 45 degrees. The average slope of these spurs is largely determined by the dip of the beds of calcareous talus breccia which mantle them, in some places up to within 100 to 150 feet of the adjacent rim crest. Especially inside the crater the lower slopes are so thickly covered with the breccia that it is difficult to determine the structure of the tuff. The lower portions of the basin are deeply covered with fine detritus which is baked and cracked in the sun giving easy access for surface water to considerable depths below the ground. The ravine channels inside the crater are much more generally choked with detritus than are those outside.

Kaimuki is a mound-like, lobate spur extending southward from the margin of the Koolau Range toward Diamond Head. The highest point exceeds 280 feet above sea level and is part of the northeast margin of a crater one-fourth mile in diameter, which occupies the center of the Kaimuki spur. The surface of the spur is made up of comparatively recent flows of vesicular, scoriaceous, and compact basalt, polygonal blocks of which remain in place over considerable areas. Beneath and around the blocks of basalt is a highly ferruginous soil of deep red color. The basalt weathers by deep pitting, which everywhere tends to be vertical rather than normal to the surface and appears to be controlled by falling rain and the retention of water. Many blocks are very rough and jagged, and ring like metal when struck with a hammer. (See Pl. VI, *D.*)

Mauumae crater is a small conical mass of coarse agglomerate and flow lava about 200 yards in diameter situated near Waialae Road and in line with Diamond Head and Kaimuki crater. Its summit rises 30 to 40 feet above adjacent parts of the range spur on the northeast and about 150 feet above the base of its own ejectamenta on the west side.

Kupikipikio Point is a small, low promontory which extends about a quarter mile out to sea beyond the general shore line east of Diamond Head. Its summit portion, which stands about one hundred feet above sea level is mantled by a recent basalt flow, and sea cliffs of five to twenty-five feet in height, form its margin (Pl. VII, *C*).

AERIAL AND STRUCTURAL GEOLOGY

General Statement

Seven principal rock formations are found in the Diamond Head region. The oldest of these is the Koolau basalt which makes up the main mass of northeast Oahu. Next younger is a complex series of calcareous reef formations which includes reef limestone, marine calcareous sandstones and conglomerates and eolian calcareous sandstones. These formations were not studied in detail but it is probable that they vary greatly in age. The Diamond Head tuff is next younger in age, followed by the Kaimuki basalt, the Kupikipikio basalt, and the Kupikipikio black ash of which the exact age relations are not known though it is believed that they were essentially contemporaneous. The youngest rock in the region, excluding modern alluvium and talus, is the calcareous talus breccia which is found on the lower slopes of the crater. It is probable that some of this is considerably older than the younger basalts and the black ash but it seems best to treat it as the youngest formation of the group.

The Reef Formations

Blocks of marine limestone are found in the tuff of Diamond Head. They occur indiscriminately in all parts of the mass as fragments 1 to 8 cm. in diameter, indicating that the vent of ejection was broken through coral limestone. Similar evidence is given by the James Campbell well, located not far from the end of the present street car line in Kapiolani Park. As reported by Hitchcock,[19] this well passes through 50 feet of surface material, 270 feet of tuff, and 505 feet of "hard coral rock." At the quarry of the Honolulu Construction and Draying Company, on Kapahulu Road, the tuff lies on an old marine bench which is mantled toward the landward edge by coarse gravel and seaward is veneered by coral reef rock and calcareous sandstone. The tuff lies directly on the gravel, though not exposed over the reef rock, no fragments of the tuff were seen in the reef rock, so it appears certain that the reef limestone is older than the tuff. All available evidence leads to the belief that limestone is generally present beneath the surface in the entire area of the Diamond Head-Kaimuki projection.

Diamond Head Tuff

The outstanding structural feature of the Diamond Head mass is the general symmetry of inclination of the beds, those outside the rim dipping radially outward and those inside dipping radially toward the center. It is important to note, however, that there are many irregularities in this gen-

[19] Hitchcock, C. H., Geol. Soc. Am. Bull., vol. 11, p. 28, 1900.

eral symmetry, that the dips are not everywhere the same, and that the maximum values are not as great as has been implied by Hitchcock. As shown in figures 13 and 14, the maximum dip is 35 degrees, readings exceeding that amount by two or three degrees being so few that they may be ascribed to errors in observation. In the higher parts of the rim many readings fell between 25 and 35 degrees and indicate that the controlling angle of rest was not far from 35 degrees at the time the tuff was deposited. Away from the crest of the rim both on the inner and outer slopes, the dip of the beds becomes less; and over the central portion of the crater bottom, as well as in areas a half mile or more outside the rim, the dips are generally less than 10 degrees.

The transition from inner to outer dips along the crater rim is not sharp. Toward the structural crest the dips become less and show a tendency to be variable or to indicate tangential plunge in one direction or the other. As the crest is passed, the dips gradually turn back to a radial direction and become greater in amount. The zone of transition from high inner dips to high outer dips is commonly 75 to 100 feet wide. At several points on the high southwest part of the rim the rounded transition may be seen in section. The arrangement of dips at certain places indicates that the deposition of the higher layers centered locally around higher points. These seem due, perhaps, to the more rapid accumulation where two different circular zones of greatest accumulation crossed each other. (See p. 25.) The most important local center from which dips tend to radiate in all directions is on the southwest rim, where drifting of ash by the trade winds was excessive. This point rises to 761 feet above sea level and the beds show a strong tangential plunge in both directions as well as the steeper radial dips toward the inside and outside.

In the region surrounding the crater but beyond its actual slopes, the dips of the tuff, while low, are generally more variable than those of the cone proper. It is evident that they are influenced to a greater extent by the configuration of the previous topography.

The areal extent of the tuff and its relation to other rocks are shown in figure 15. At the quarry of the Honolulu Construction Company 1 to 5 feet of tuff is exposed, underlain by weathered gravel composed of cobbles of Koolau basalt and overlain by Kaimuki basalt, 4 to 9 feet thick. A similar thickness of the tuff is found beneath the Kupikipikio basalt at the southeast extremity of Kupikipikio Point. At these two localities the tuff is at the greatest known distances from its source.

The tuff overlying a marine bench about 35 feet above sea level at the quarry of the Honolulu Construction Company seems to indicate the posi-

tion of the sea at the time of the Diamond Head eruption. That the sea continued in this relation for some time after the eruption is suggested by the presence of a buried wave-cut cliff along the south and southwest flanks

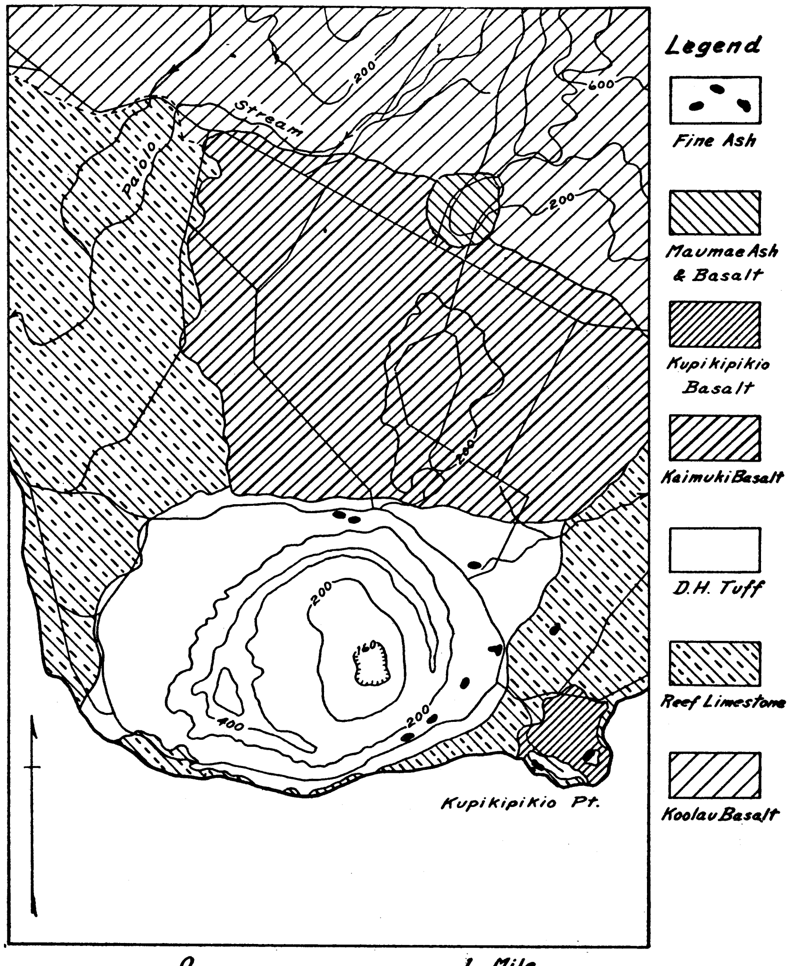


FIGURE 15.—Map showing areal geology of the Diamond Head district.

of Diamond Head having its notch at approximately the same elevation. In several ravine sections on this side of Diamond Head the talus breccia formation lies on a gently sloping bench of tuff, banked abruptly against a tuff cliff which rises at angles of 45 to 70 degrees from its junction with the bench. At another point slightly nearer the sea and at a lesser elevation, the tuff bench is overlain unconformably by eolian calcareous sandstone

showing characteristic eolian bedding. At several other points still nearer the coast, the same bench is overlain by marine sandstone and conglomerate. On the present beach pavement, which is being scoured and channelled by the waves, are inlaid remnants of well cemented marine sandstone which lie in furrows, potholes, and sea urchin borings formed at an earlier time by shore processes. The retreat of the sea from the 35-foot level is indicated by these data.

Diamond Head Talus Breccia

Talus breccia mantles extensive areas of the slopes of Diamond Head with thicknesses of 5 to 25 feet, exceptionally 50 feet. It extends to within 100 feet vertically of the rim crest on some of the spurs though it does

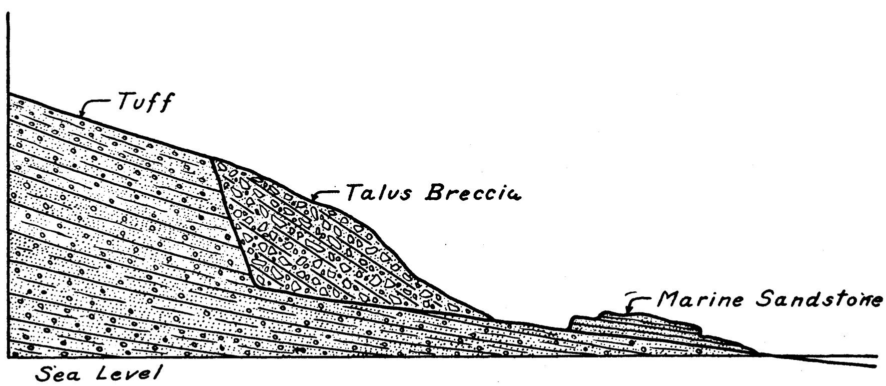


Figure 16.—Generalized section showing relations between tuff, talus breccia and marine calcareous sandstone on the seaward flank of Diamond Head.

not cover considerable areas above the 200-foot contour line. The bedding, crude and irregular, is shown chiefly by the calcareous laminae which separate the materials accumulated during different stages of deposition. The dip of the beds is everywhere closely parallel to the existing topographic slope, and ranges from 30 degrees on the higher slopes to 10 degrees, or less, at lower elevations where the material is in part water borne. In their upper courses the principal ravines of the Diamond Head slopes are cut through the breccia into the tuff. In their lower courses, on the contrary, the channel is commonly in the breccia and exposures of the tuff are relatively difficult to find. In ascending ravines on the seaward side of the crater the breccia is found to outcrop commonly to some distance northward of the highway. The tuff is here encountered abruptly, the contact between the two rocks rising at angles of 40 to 70 degrees. (See fig. 16.) The elevation of the base of this steep contact was not determined pre-

cisely; but by combining data obtained in a number of the ravines, it is found that the marine bench cut on tuff and mantled at different places with marine detrital limestone, eolian detrital limestone, and talus breccia ends abruptly at elevations of 25 to 30 feet and gives way to a relatively steep sea cliff which is now deeply overstrewn with talus breccia (Pl. VI, *B*).

The talus breccia is composed of angular fragments of tuff cemented into a porous but fairly compact mass. Most of it was accumulated wholly under the action of gravity. At a few places on lower slopes below 100 feet, this phase grades seaward into rudely assorted material which was probably accumulated by the action of ephemeral slope wash; and this material in turn grades into a tuff conglomerate, which is a phase of the detrital marine limestone (p. 117). (See Pl. VI, *A*.)

Kaimuki Basalt

No detailed study was made of the basalts of Oahu except with respect to the light they throw on post-Diamond Head history. From this standpoint their relations to the other rocks of the area were determined and note taken of their outstanding features.

The Kaimuki basalt varies from a dense rock nearly free from vesicles to very scoriaceous material with abundant cavities two centimeters in diameter. It was extruded from the small crater which occupies the center of the Kaimuki spur and no part of the flow reached more than about a mile and a quarter from the vent. The entire area covered by the Kaimuki basalt is strewn with rough, pitted blocks which are weathered to a deep red color. In the central parts of the areas covered by the various streams of lava many of the blocks lie in their original positions and are separated by a characteristic rough polygonal system of joints. The field relations suggest that the Kaimuki basalt is younger than the Diamond Head tuff. A clear exposure showing transgression of the lava over the tuff may be seen at the quarry south of Kapahulu Road (Pl. VII, *B*).

The weathering shown by the tuff beneath the basalt indicates that the two rocks are not of approximately similar age.

Kupikipikio Basalt

The Kupikipikio basalt flow covers the higher part of the Kupikipikio promontory. Parts of its original surface made up of polygonal columns are still intact and over the remaining parts the numerous ragged blocks are only slightly disturbed. It is weathered in similar degree to the Kaimuki basalt and is believed to be of the same age. Megascopic examination shows this basalt to be similar to the Kaimuki basalt. Evidence is lacking for any

surface connection between the two flows. A dike which reaches the coast at the shore angle just west of Kupikipikio Point suggests that this lava issued from a short fissure at this point at the time of the Kaimuki eruption. A short distance eastward a dike 4 inches to 2 feet in thickness cuts the coral reef and the shore limestones in an irregular line which runs out to sea (Pl. VII, *A*). The Kupikipikio basalt is the source of the boulders of the coarse reef conglomerate and of the modern shore boulders (Pl. VI, *C*). The lower parts of the shore limestones appear to be free from the basalt detritus whereas the upper parts are conspicuously conglomeratic, suggesting that the limestones are in part older and in part younger than the basalt.

The relation of the basalt to the Diamond Head tuff is well shown at the extreme southeastern point where the basalt overlies the tuff in the modern sea cliff. At a number of other places on the point, similar relations exist which are less exposed.

Mauumae Volcanics

Mauumae was the source of materials ranging from medium textured black ash through coarser agglomerate and rhyoclastic lava to flow lava. In general, the finer and true pyroclastic material was ejected first, and such flow lava as was later ejected assumed the steep angle of rest of the earlier materials and, so far as known, nowhere reached the base of the cone.

Black Ash

At a number of places on the lower slopes of Diamond Head and around the shores of Kupikipikio Point, are thin patches of fine-grained black ash (fig. 15). This ash is only slightly cemented and is both overlain and underlain by talus breccia. It has nowhere been found in definite relationship to the basalts and its age cannot therefore be determined more precisely than that it is much younger than the tuff. It seems probable that it is contemporaneous with the basalts and either issued from the same vents as an auxiliary phase of the eruption; or, as seems more likely, came from the small crater Mauumae north of Waialae Road, which is known to have been a source of considerable pyroclastic material.

The Volume of the Tuff and Mechanics of Eruption

The total volume of tuff composing Diamond Head was roughly computed by Bishop as thirteen billion cubic feet. An independent estimate made for the present study places the total volume approximately at twenty-

one billion cubic feet. The difference in the estimates is due chiefly to the assumptions adopted for the lower limit of the tuff and for its southwestward limit. The present estimate is based on the following considerations: The tuff lies on an old marine bench at about 30 feet above sea level at the quarry near the corner of Waialae Road and Kapahulu Street. Its base in the James Campbell well near the end of the Waikiki car line is 300 feet below sea level. It seems probable that the slope is nearly uniform between the two places and that the strike of the marine bench is about

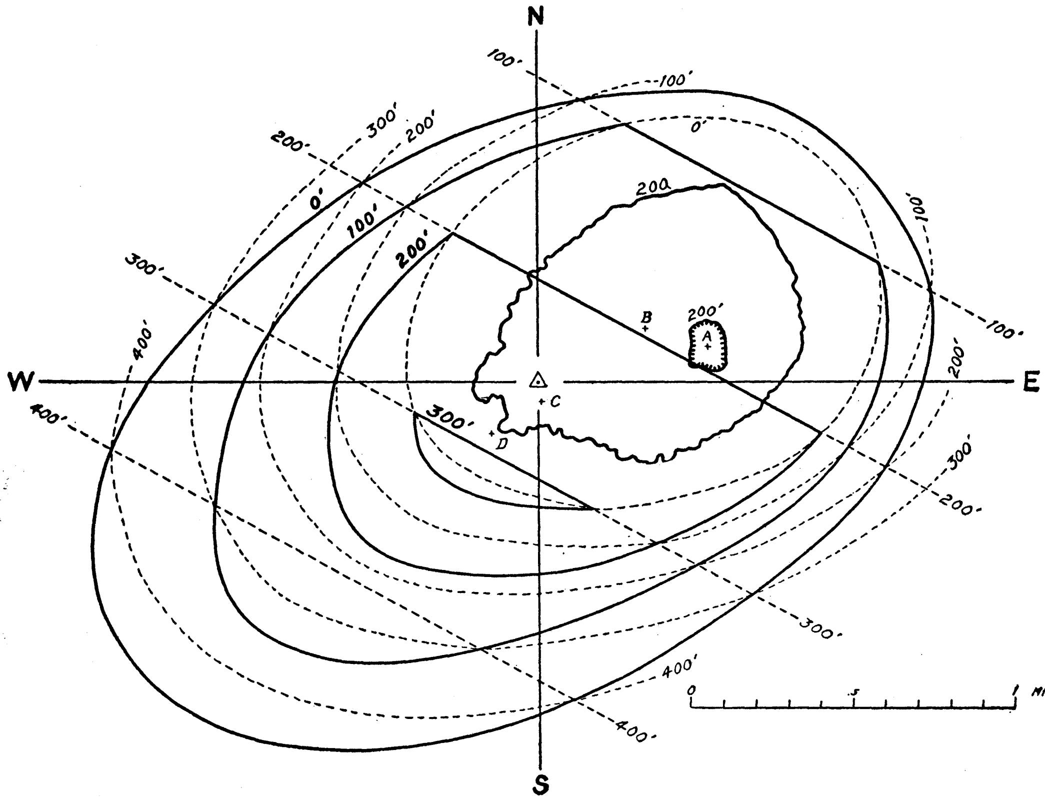


FIGURE 17.—Diagram illustrating the computation of volumes and center of gravity of several parts of the Diamond Head mass. The 200′ contour line, both inside and out is shown for aid in orientation. The parallel straight lines trending about N. 62° W. show depth of the assumed sloping submarine pavement described in the text. The oval light dotted lines are submarine contours on the assumed Diamond Head mass. The heavy solid lines following the straight lines in part and passing through intersections of the parallel straight lines and oval dotted lines are isopachs (lines of equal thickness) of the submarine part of the tuff. *A* is the lowest part of the present crater basin; *B* is the center of gravity of the subaerial part of the tuff, and *C* the center of gravity of the entire mass, as computed under the assumptions described in the text. *D* is the center of gravity of the submarine part.

parallel to the line of the truncated spurs of the Koolau Range. Therefore for the purposes of computation the base of the ash was taken as a plane standing 30 feet above tide level at the Kapahulu Quarry and 300 feet below tide at the James Campbell well and having a strike parallel to the Kaimuki portion of Waialae Road, or about N 62° W. The portion of the Diamond Head cone above 40 feet is well delineated by the surface contours. By continuing the slopes of the cone downward, allowing for the existing changes of slope as well as the actual slope, data were secured for drawing the sea level contours and the submarine contours at hundred foot intervals on the upper surface of the tuff. In the direction of the greatest accumulation (southwest) the finding of the upper surface of the ash at about 30 feet below sea level was used as a most valuable datum in controlling the configuration. By combining these data on upper and lower surfaces of the ash, the isopachs (thickness contours) shown in figure 17 were constructed. These were used for the submarine portion and the surface contours for the supermarine portion in computing volumes. The smaller areas were measured by means of a polar planimeter, and the larger by cutting out and weighing cardboard of uniform thickness, the areas being expressed in square miles. Volumes were computed by the formula

$$v = \frac{h\,(a + 4m + b)}{6}$$

when h is height of prism
a and b are areas of end sections
and m the area of section midway between the ends.

The results are shown in Table 1.

TABLE 1. VOLUMES IN MILE-FEET (1 FOOT THICKNESS OVER ONE SQUARE MILE)

Above sea level	700-761 feet	.02
	600-700 "	.39
	400-600 "	7.54
	200-400 "	56.20
	0-200 "	179.20
		243.35 mile-feet
Below sea level	0-100 feet	310.00
	100-200 "	168.00
	200-300 "	44.50
	300-315 "	.20
		522.70 mile-feet
		243.35
		522.70
	Total	766.05 mile-feet

Converting into cubic feet and rejecting all but three significant digits the figure is:

$$766.05 \times 5280 \times 5280 = 21{,}400{,}000{,}000 \text{ cubic feet.}$$

The center of volume of the tuff was determined by cutting out cardboard having the outlines of each of the prisms measured above, and determining its center of mass by suspending it from a pivot in each of two positions and marking the vertical through the pivot. The centers of mass (and of volume) were then combined in pairs and reduced to the positions shown in figure 17 for the submarine, supermarine, and combined volumes.

The idea of extremely rapid and nearly continuous expulsion of pyroclastic material completing the formation of Diamond Head in one episode is due to Bishop. Though objected to by a number of geologists, notably W. H. Dall,[20] the conclusions of Bishop are supported by Hitchcock [21] and, in so far as they postulate a rapid, uniepisodal origin for Diamond Head, are entirely in accord with the results obtained by the present study. Little attention has been given by modern workers to the mechanics of deposition or to the interpretation of the critical stratigraphic features. The earlier geologists, presumably following Dana, seemed generally to hold the view that the tuff was expelled from the vent in the form of hot mud, and interpreted the general red-brown color to mean that the temperature was not over 200° F. This view finds no support in the general structure and bedding of the crater. Apparently the tuff was expelled in a dry condition, or at least in the condition of minutely dispersed particles containing only water which largely evaporated prior to deposition, or water which took part in the process of alteration which produced palagonites from original glass. Moreover, the red-brown color so characteristic of the tuff is the result of the secondary palagonitization, which is believed to have taken place mainly, if not wholly, after the material was deposited and can therefore hardly be indicative of the temperature of expulsion.

The two principal features which indicate essentially dry deposition of the tuff are the high angles of rest shown in the crest portions of the crater rim and the very uniform character of the bedding found throughout the entire mass of tuff. The dip of the bedding, 30 to 35 degrees, is precisely that common in the finer grained dry detrital materials. So far as known, the finer grained detrital sediments never accumulate under water at angles greater than about 25 degrees, commonly somewhat less. Similar angles would be expected in materials not deposited under water but con-

[20] Dall, W. H., Notes on tertiary geology of Oahu: Geol. Soc. Am., vol. 11, p. 58, 1900.

[21] Hitchcock, C. H., Geology of Diamond Head: Geol. Soc. Am. Bull., vol. 17, pp. 469-484, 1906.

taining considerable water and deposited as a mud. If a very great amount of water were present, very much lower angles would be expected. If it be urged that the material contained just enough water to give it maximum viscosity and thus to sustain angles of 30 to 35 degrees, there should be clear evidence in the bedding of this viscous character. Such material would be expected to accumulate in irregular masses and heavy, thick flows showing crude overlapping and lenticular structures. These are not found in the Diamond Head mass. A dry condition is shown also by the absence of the features likely to be developed in any sort of aqueous deposition. The accumulation of detrital material at angles exceeding 5 degrees would be expected to develop at least some such features as cross-bedding, overlapping, clean sorting of some layers, and cut and fill structures. Such features are particularly likely to result from tumultuous deposition adjacent to a restricted source, such as the Diamond Head vent. None were observed. If, on the other hand, the tuff had been deposited in wet condition but not subaqueously, the water drained off the slopes would have left clear marks in such features as channeling, cross-bedding, and fans. The conclusion is that the Diamond Head tuff was deposited, so far as the exposed parts are concerned, wholly in air and in a dry condition. This conclusion lends indirect but substantial support to the hypothesis of Bishop, which is applicable to a dry eruption but not to a wet one.

Bishop [22] computed the velocity of expulsion, the height projection, and duration of the eruption but did not, so far as known, describe the methods and assumptions underlying his computations. It seems desirable to consider the problem from this standpoint. It was assumed with reason by Bishop that the regularity, symmetry, and comparative sharpness of crest of the circular crater rims of the Diamond Head type postulate practically constant conditions of projection from the vent during a single brief episode. It seems unlikely that after any considerable interval a second episode would so nearly duplicate the first, as to add with precision to the accumulated debris of a previous eruption. On this assumption, the problem becomes that of determining the factors which would control delivery of the material on the crater rim and the optimum values of these to match the actual size of the rim. The more important factors are:

(a) Velocity of projection
(b) Angle of projection
(c) Velocity of wind

Factors (a) and (b) may be restated in the form of (1) vertical velocity and (2) horizontal velocity. The vertical velocity of the issuing projectiles

[22] Bishop, S. E., Geology of Oahu, Hawaiian Annual for 1901, Honolulu, 1902.

is shared by the velocity of a large volume of gases. The horizontal velocity may be in part the horizontal component of a velocity of projection (a) which has an angle other than 90 degrees, or it may be due to the horizontal acceleration of expanding gases within the rising column. The wind velocity, with its variations at different elevations, operated in two essential ways: first, in adding a general horizontal acceleration in its direction of motion, which was a negative factor on the windward side and a positive factor on the leeward in affecting the delivery of the projected material to the rim crest; second, in causing a much more extended leeward shift of the finer materials which acted not even approximately as projectiles but were carried for some time in the air before settling.

The data are so incomplete and the conditions known with so little precision that an elaborate mathematical treatment seems unwarranted. But by using simplified assumptions, the effects of the various factors may be computed and probable orders of magnitude be established by separating absurdly high from absurdly low results.

Two independent modes of approach were used. In the first it was assumed that

1. The materials followed the laws of projectiles and reached the crater rims by parabolic paths.
2. That air resistance (absent during a part of the period of rising) was negligible.
3. That by using the mean distance of the rim crest from the supposed eccentric position of the vent, the effect of the wind would be practically eliminated; and also that errors due to ignorance of the true position of the vent would be largely cancelled.

Based on these assumptions the minimum, mean, and maximum range (distance of rim crest from supposed position of vent) were calculated as in Table 2.

TABLE 2.—VELOCITIES IN FEET A SECOND, CORRESPONDING TO RANGES

ANGLE OF PROJECTION	MINIMUM RANGE 1050 FT.	MEAN RANGE 1875 FT.	MAXIMUM RANGE 2900 FT.
90	inf	inf	inf
89	986	1315	1634
88	697	930	1155
87	570	760	944
86	493	658	867
85	442	589	732
80	313	417	518
75	259	345	429
70	229	306	380
65	210	280	346
60	198	264	327

The principal source of error in these figures is probably the unknown effect of horizontal dispersal due to the expansion of the rising gas column. This would tend to effect delivery of the projectiles at the crater rim with lower velocities than would be required if it were absent. If this possible effect be ignored for the moment and attention given to the table, it will seem that the range of velocities for the mean distance is from 264 feet a second for 60 degrees, to 1,315 feet a second for 89 degrees, and rising to infinity at 90 degrees. Granting that direct discharge from the vent at a lower angle than 70 degrees is improbable and that a general discharge of the bulk of the material at closer to the vertical than two degrees is equally unlikely, it is possible to segregate the most probable values of the velocity as between 306 and 930 feet a second, or in round numbers and a slightly increased ratio, from 250 to 1000 feet a second.

In determining the duration of the eruption from these figures, it is necessary to assign certain probable values for the cross sectional area of the vent and for the percentage of solid material by volume issuing from it. A vent less than 50 feet in diameter is hardly compatible with the large amount of material which has been derived from it or with the high velocities (even under the most adverse assumptions) which must have obtained. One of 200 feet in diameter enormously reduces the duration of the eruption and may well serve as the other extreme. The cross sectional areas of vents of these dimensions are 1,962 and 31,416 square feet, respectively. The percentages of solid material in the total expelled volumes may be taken as ranging from 20 to 60 per cent with reasonable assurance that the true value is included between them. The total volume of the Diamond Head tuff was computed as approximately 21,000,000,000 cubic feet. The results of combining these figures in the formula

$$T = \frac{21{,}000{,}000{,}000}{V\ (\text{vent area})\ (\text{ratio solid material})}$$

are shown in Tables 3, 4, 5, in which slight discrepancies in ratios are due to the dropping of fractional minutes.

TABLE 3.—DURATION OF ERUPTION IN HOURS AND MINUTES, 60 PER CENT SOLID MATERIAL

VELOCITY OF ISSUE, FEET A SECOND	VENT DIAMETERS		
	50 FT.	100 FT.	200 FT.
1000	4-57	1-14	0-19
500	9-55	2-29	0-37
250	19-49	4-57	1-14

TABLE 4.—DURATION OF ERUPTION IN HOURS AND MINUTES, 40 PER CENT SOLID MATERIAL

VELOCITY OF ISSUE, FEET A SECOND	VENT DIAMETERS		
	50 FT.	100 FT.	200 FT.
1000	7-26	1-51	0-28
500	14-52	3-43	0-56
250	29-44	7-26	1-51

TABLE 5.—DURATION OF ERUPTION IN HOURS AND MINUTES, 20 PER CENT SOLID MATERIAL

VELOCITY OF ISSUE, FEET A SECOND	VENT DIAMETERS		
	50 FT.	100 FT.	200 FT.
1000	14-52	3-43	0-56
500	29-44	7-26	1-51
250	59-28	14-52	3-43

The tables show a variation in duration from a minimum of 19 minutes to 59 hours and 28 minutes, or 192 fold. Of the 27 values given, two-thirds, or 18, indicate a duration of 1 to 15 hours; the average for the entire 27 being 9 hours and 16 minutes; the average for the 18 falling between 1 and 15 hours, is 6 hours and 2 minutes.

In the second mode of approach to the problem, it was assumed that the eccentricity of the rim circle with respect to the supposed position of the vent (the center of the interior 200-foot contour) was due to the trade wind drift. Or as a similar proposition, that the separation of the center of volume of the Diamond Head mass from the position of the vent represents the amount of trade wind shift. If this assumption is valid, and an average velocity for the trade winds throughout the elevations reached by the projected material is assumed, it is possible to deduce the length of time the individual particle was in the air; and thence by applying the law of falling bodies, determine the velocity of projection. In using the center of mass as a factor, only that material above sea level, much of which is concentrated in the definite crater cone, was considered. The submarine portion was neglected. While this is a purely arbitrary separation, some such separation is justified by the two types of material thrown out. Much of the finer material settled so slowly, that the time it remained in the air is no index of the velocity of ejection. This material largely drifted out beyond the main crater cone and the bulk of it apparently settled southwest of Diamond Head. It is this material which makes the center of volume of the submarine part of the tuff lie so far to the southwest, a fact which somewhat justifies ignoring this part of the mass in computing the trade wind drift as a measure of duration of flight of the coarser material.

The eccentricity of the rim circle is approximately 925 feet, and the separation of the center of volume of the supermarine portion of the tuff from the vent is approximately 1050 feet. If this distance be resolved into its component parallel to S 70° W, it will be found to be about 855 feet. The average trade wind velocity is about 12 miles an hour, and 10, 20, and 40 miles an hour include the probable range. Using these values, the duration of flight and velocities have been computed in Tables 6 and 7.

TABLE 6.—DURATIONS OF FLIGHT IN SECONDS

TRADE WIND VELOCITY	DISTANCE OF DRIFT		
	855 FT.	925 FT.	1050 FT.
10	58	63	72
20	29	32	36
40	15	16	18

TABLE 7.—VELOCITIES CORRESPONDING TO DURATIONS OF FLIGHT SHOWN IN TABLE 6

DURATION OF FLIGHT IN SECONDS	VELOCITIES, FEET A SECOND
72	21,000
63	16,000
58	13,500
36	5,200
32	4,100
29	3,400
18	1,300
16	1,000
15	900

These velocities are much higher than those deduced in the computation by the first method used. Only the higher trade wind velocities bring the velocities of projection within the range indicated. In so far as this method of approach is a valid check on the other method, it points to higher velocities and lower values for the duration of eruption. The duration suggested by these higher velocities are shown in Tables 8, 9, and 10.

TABLE 8.—DURATION OF ERUPTION IN MINUTES AND SECONDS, 60 PER CENT SOLID MATERIAL

VELOCITY OF ISSUE, FEET A SECOND	VENT DIAMETERS		
	50 FT.	100 FT.	200 FT.
1,000	398-0	74-0	18-35
2,000	149-0	37-0	9-17
4,000	74-0	18-35	4-39
8,000	37-0	9-17	2-19
16,000	18-35	4-39	1-9

TABLE 9.—DURATION OF ERUPTION IN MINUTES AND SECONDS, 40 PER CENT SOLID MATERIAL

VELOCITY OF ISSUE, FEET A SECOND	VENT DIAMETERS		
	50 FT.	100 FT.	200 FT.
1,000	446-0	111-0	28-0
2,000	223-0	56-0	13-56
4,000	111-0	28-0	7-58
8,000	56-0	13-56	3-59
16,000	28-0	7-58	2-0

TABLE 10.—DURATION OF ERUPTION IN MINUTES AND SECONDS, 20 PER CENT SOLID MATERIAL

VELOCITY OF ISSUE, FEET A SECOND	VENT DIAMETERS		
	50 FT.	100 FT.	200 FT.
1,000	892	223	56
2,000	446	111	28
4,000	223	56	13-56
8,000	111	28	7-58
16,000	56	13-56	3-59

The average of the values given in Tables 8, 9, 10, is 1 hour and 33 minutes, and the geometrical mean between the extremes is approximately 32 minutes. Values falling between 10 minutes and 2 hours are 25 in number; they average 49 minutes.

The effect of correcting the durations shown in Tables 3, 4, 5, for the effect of horizontal dispersal within the rising column of gas would be to decrease the velocities and to increase the duration of eruption.

It is believed that the figures given in Tables 3, 4, 5 more nearly represent actual conditions than do those in Tables 8, 9, 10. The conclusion is drawn, therefore, that the duration of eruption of Diamond Head was of the order of five hours. The eruption may have been intermittent with interruptions sufficient to extend the whole period of activity to as much as five days, but probably not more.

Summary of Geologic History

Following the erosion of the Koolau Range and the formation of a long line of sea cliffs extending from Makapuu Head to Pearl Harbor, the eruption of Diamond Head took place. At this time the sea stood about 40 feet higher than now and the present site of Diamond Head was covered in part at least with off-shore coral reefs. It is probable that tuff was deposited on the coral in the area north of Diamond Head in amounts

sufficient to connect the crater with the main mass of Oahu by a neck of land. From what is known of the configuration of the Kaimuki lava it seems unlikely that this connection was broken before the formation of the Kaimuki crater.

The sea remained about 40 feet higher than now for a rather brief period, while cliffs were cut in the tuff and then receded to a position not more than 12 feet above the present level.[23] On the slopes of Diamond Head considerable quantities of talus breccia were formed and cemented by calcium carbonate.

With the renewal of volcanic activity, the main vent of Diamond Head remained dormant, but three other vents not known to have been active previously opened, those of Kaimuki, Mauumae, and Kupikipikio. Kaimuki and Kupikipikio are not known with certainty to have yielded pyroclastic materials, but Mauumae emitted considerable ash. Absolute proof of the simultaneous action of these three craters is lacking, but from the facts that two of them are known to be post-Diamond Head and poured their lavas in similar relations over the weathered Diamond Head tuff, and that all three are of similar character it seems very probable that they acted nearly in unison. The lavas of Kaimuki and Mauumae established two crater masses and the Mauumae lavas made more permanent the neck of land which joins Diamond Head to the Koolau Range. Lava from the Kupikipikio dike added considerably to the height of Kupikipikio Point and gave greater stability to the original reef rock mass over which it was erupted. Recession of the sea to its present position and the continuation of weathering and erosion to the present day are the closing geologic events of the Diamond Head region.

PUNCHBOWL CRATER

GENERAL RELATIONS

Next to Diamond Head, Punchbowl (Puuowaena) is the most conspicuous and best known of the secondary craters of Oahu; its slopes constitute one of the residential districts of Honolulu.

Punchbowl is a nearly circular tuff crater having a diameter from crest to crest of about three-eighths mile and a basal diameter of about three-fourths mile (Pl. VIII). About three-fourths of its rim stands more than 400 feet above sea level and several small summits on the west part of the rim exceed 480 feet. Except on the side toward the Koolau Range, Punchbowl rises with steep slopes from a plain 60 to 80 feet in elevation. The

[23] Wentworth, C. K. and Palmer, H. S., Eustatic bench of islands of the North Pacific: Geol. Soc. Am. Bull., vol. 36, pp. 521-544, 1925.

interior of the crater, an area of about 60 acres, is drained through a breech in the crater wall on the southeast. The flatter portion of the crater bottom lies between 325 and 400 feet above sea level.

Punchbowl appears to have been an isolated center of eruption. No other crater is closely associated with it. At the northeast, Punchbowl is separated from the Pauoa-Makiki range spur by a low gap in which the crater is seen to be banked closely against the end of the spur.

In its topographic expression Punchbowl is similar to Diamond Head but its slopes are less precipitous. Radial gullies, most of them less than 50 feet deep, drain the outer slopes on the western and southern sides. Near their heads are steep or nearly vertical walls a few feet high, but nearly the whole outer slope of Punchbowl is accessible to pedestrians. There are no precipitous slopes on the inside of the crater and no well developed radial gullies. The southeast crater wall is broken down to the level of the interior floor and at this breech heads a deep gulch of high gradient, which, turning from a southeasterly to an easterly course, drains out onto the coastal plain. The slopes of Punchbowl both inside and out are generally covered with vegetation, cactus and kiawe being the most conspicuous plants.

GEOLOGIC FEATURES

In addition to the Koolau basalt which underlies and flanks, the crater on its northeast, Punchbowl consists of three rock formations. The oldest of these is the tuff which makes up the main mass of the crater. The second and third are the closely associated black ash and basalt of much more recent date.

The Punchbowl tuff is exposed at the surface over an area of considerably less than a square mile (fig. 18). It is known in a few drill holes beyond the margin of its surface exposure but its thickness decreases rapidly and it probably is negligible in amount at a distance of two miles from the center of the crater. In the well at Queen's Hospital the tuff extends from about sea level downward for 47 feet. In the wells at the pumping station (Alapai and Beretania streets) a total thickness of about 50 feet of tuff has its upper surface at about sea level. From what is known of the rate of decrease in thickness with increasing distance from the vent, it is probable that the original thickness of the tuff at a distance of a mile was not more than two feet, even in the direction of trade wind transportation.

The structure of Punchbowl, next to Diamond Head, is the most simple and ideal of all the craters on Oahu. In general, the rim of the crater is

made up of beds which dip radially outward on the outside and inward on the inside. Close to the crest of the rim dips are commonly from 30 to 35 degrees; 200 to 300 feet below the crest the dips on the outer slope are 15 to 25 degrees. Beds now exposed on the southwest crest of the rim dip generally inward, those on the northeast crest generally outward. This lack of correspondence between the structural and topographic crests may be due in part to erosion, but probably is mainly due to a slight reduction

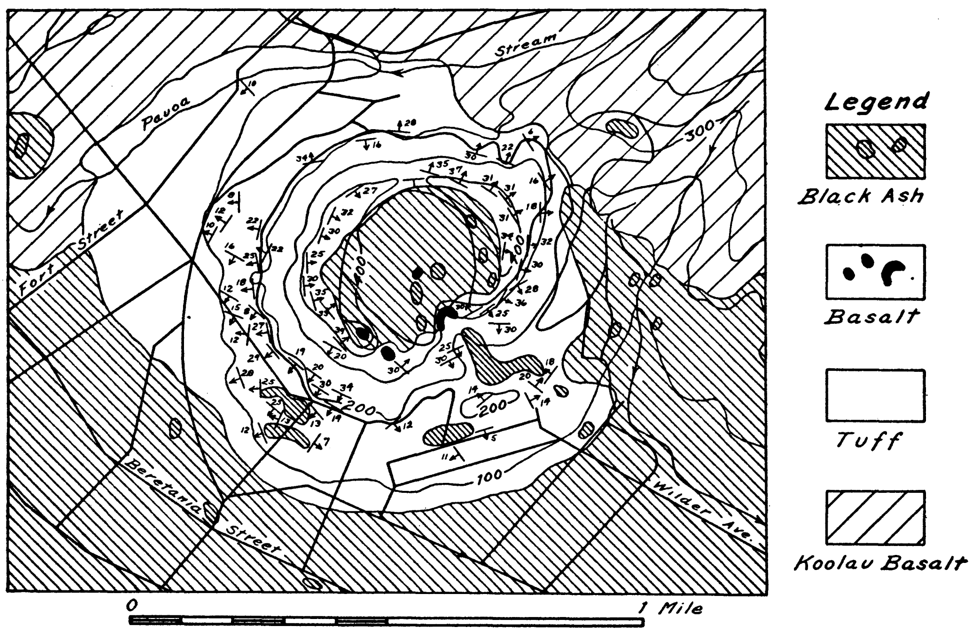


FIGURE 18.—Map showing areal geology of the Punchbowl district.

in the velocity of the trade winds toward the close of the eruption and the consequent excessive mantling of the northeast facing slopes of the newly formed crater. North of Spencer Street, beds of tuff with radial dips are mantled on what was some sort of pre-existent eminence. Except on the immediate crest, the tuff of the interior of the crater bowl is mantled with colluvium and with black ash, and its structure is not known in detail.

The Punchbowl tuff is of the typical palagonitic variety. No partly altered ash was seen in the Punchbowl mass. As compared to Diamond Head, the tuff of Punchbowl is somewhat coarser, contains somewhat larger and more abundant basalt bombs, is more conspicuously mottled with secondary aragonite and calcite, and in general is more weathered, giving the appearance of greater age. To what extent these features are due to

greater age and how much to more favorable conditions for weathering is not known with certainty, but probably weathering is the determining factor. In a few deep cuts the tuff appears very compact and semi-vitreous. In the channel of Pauoa stream it shows well developed spheroidal weathering, which is much more nearly like that commonly found in basalt than that of most tuff masses (Pl. X, *C*).

At numerous localities on the flanks of Punchbowl, small masses of fine or medium black ash lie unconformably in channels eroded in the tuff. The typical structural relations are shown in figure 19. Black ash is found also at nearly all the excavations which have been made for roads or target

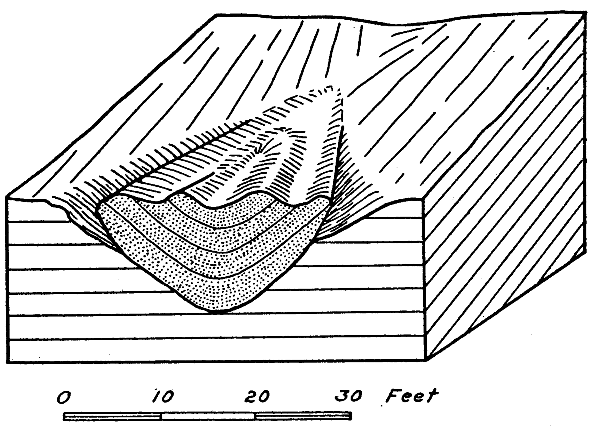


FIGURE 19.—Block diagram showing typical relations of black ash remnants lying in old ravines cut in Punchbowl tuff.

trenches inside the crater bowl. A large mass of black ash lies deep down in the channel of the gulch which extends southeastward from the breach in the rim by which the bowl is drained. Because of the fact that large amounts of black ash ejected by the craters in the Tantalus region lie to the eastward of Punchbowl and extend to its flanks, it is not possible to attribute all the ash found on its slopes to ejection from the Punchbowl vent. However, observations on the south and southwest crest of the rim show that Punchbowl was the source of some of the black ash. Just outside the junction of the road loop on the south rim, black ash lies with indipping beds on the tuff. A few feet higher stratigraphically this black ash grades into droplet rhyoclastic material, and that in turn into true flow lava in fairly dense masses having the same indipping structure. It is quite clear that the black ash, rhyoclastic material, and flow lava are part of a closely contemporaneous series.

Similar relations in age and materials are shown by the resistent lip of the breach in the crater rim, where a mass of flow lava and rhyoclastic material lies in an erosion channel obviously cut since the Punchbowl tuff was deposited. These facts establish the considerable difference in age of the tuff and the black ash which are in contact with apparent conformity at the road loop on the rim, and are in accord with the unconformable relations found between the black ash and the tuff on the lower flanks of the crater.

GEOLOGICAL HISTORY

The Punchbowl tuff was erupted from a vent which penetrated coral reef formation at a point close to the margin of the Koolau Range. The surface of the reef at the time of the eruption was about 50 feet below present sea level at the outer margin of the Punchbowl crater. In the well at Queen's Hospital, 13 feet of coral lies above the tuff with the contact practically at sea level. The tuff was apparently erupted either before or during the epoch when Oahu was submerged 35 to 40 feet more than at present. If the eruption took place during such submergence, there would have been a depth of about 80 to 90 feet of water a half mile off shore. This is by no means an improbable depth, especially since the points in question are in the direct line of the original Pauoa channel and there may have been at that time a break in the growing reef at that point. It is not clearly indicated by the evidence that Punchbowl is older than Diamond Head but rather that it cannot be younger and may be older.

The symmetry of the Punchbowl crater and the homogeneity of its material indicates that, like Diamond Head, the eruption was a single brief pyroclastic episode, perhaps lasting but a few hours and at most not more than a few days. After the formation of the cone, erosion of its slopes went on for a considerable period until they were deeply channeled and until a minor branch of Makiki stream had worked headward and cut through the rim on the southeast side.

Following this erosion, a second eruption took place in which black ash was first ejected and then progressively more fluid material, until a small amount of flow lava had reached the surface. The lava was sufficient in amount to flow a few yards and to spill over the break in the crater wall but none of it apparently moved down the gulch outside the rim. Erosion has now largely stripped the black ash from the outer slopes of Punchbowl and the surface of the black ash inside the crater is extensively weathered. From the relation of the black ash to the tuff on the flanks of the crater there is reason to believe that the larger part of the dissection of the tuff crater had been accomplished before the eruption of the black ash. From

the distribution of black ash on coral reef at a number of wells in the city at elevations less than 30 feet above sea level, it seems not improbable that the eruption of the ash, much of which is from the Tantalus craters, took place after the sea had receded to a position 10 to 12 feet above present sea level. With lack of contrary evidence this interpretation is applied to the Punchbowl black ash and the associated basalt.

THE SALT LAKE CRATERS

GENERAL RELATIONS

The Salt Lake craters are the westernmost centers of recent pyroclastic activity in Oahu. They are situated on the landward edge of the low peninsula between Kalihi Entrance and Pearl Harbor, about five miles northwest of the center of Honolulu. The group consists of three craters, Salt Lake (Aliapaakai), Aliamanu, and Makalapa (fig. 6). Tuff of two ages is spread over a considerable area to the south and west of the craters, forming by far the most extensive exposure of pyroclastic rocks on the island.

Salt Lake crater has been the site of a body of brackish or salt water for as long as it has been known to Americans. At the time of Dana's visit (1840) the water was at or very near sea level and was reported to be affected to a slight extent by the tides. The lake was then but a few inches deep and its bottom was heavily encrusted with salt crystals. An artesian well bored some years ago on the shore of Salt Lake with the object of freshening the water for fish culture, discharges into the lake, and a tunnel now carries the surplus water from Aliamanu to Salt Lake. From these two sources Salt Lake derives a considerable supply of water and in December, 1923, its surface stood at an elevation of 20.25 feet above sea level. Makalapa crater, mentioned as a flat plain by Dana, is now the site of a small storage pond.

FORM AND SIZE OF THE CRATERS

Salt Lake is about 0.8 mile long and 0.7 mile wide. The crater rim which surrounds it measures about 1.4 miles by 1 mile. At the southwest the rim is not more than 50 to 60 feet high, but in several places it attains elevations of 200 feet, and at the northwest a peak, more properly a part of the rim of Aliamanu, reaches 360 feet above sea level. As reported by Dana, the bottom of the crater is flat and lies almost precisely at sea level. The Salt Lake rim differs markedly from many of the craters of other groups by its broad, low cross section and general lack of a high

ridge with precipitous slopes. The outlines of the lake basin as well as of the anticlinal ridges shown in the structure of the tuff indicate that the Salt Lake is a compound crater. In fact, the adjacent Aliamanu crater may also be considered a part of this larger crater, which thus had at least four explosive centers.

Aliamanu is about 1.2 miles long in an east-west direction and 0.7 mile wide. It is surrounded by a definite, sharp-crested rim which is nowhere less than 100 feet in elevation. A point on the south rim is 400 feet high, and the northeast rim culminates in a sharp peak at 485 feet. These two points, one inland and the other seaward of Aliamanu, are the most conspicuous of the topographic features of the Salt Lake region as seen from a distance. The bottom of the crater with an area of about one-third square mile is a flat plain standing about 40 feet above sea level. It is at present planted to sugar cane.

Makalapa crater resembles Salt Lake crater in its low, nearly flat topped crater rim and also (at present) in its contained body of water. It has a nearly circular outline of about one-half mile in diameter. The elevation of the rim varies from 30 to 60 feet above tide.

Salt Lake is drained entirely by seepage. Before the introduction of artesian water and of irrigation water drained from Aliamanu the lake was so effectively drained by this means that its level was but a few inches above mean sea level. At present, with the increased inflow, a head of about 20 feet above sea level is maintained.

Regarding the source of the salt water, Alexander[23a] writes:

> The belief in a connection with the ocean through a large hole in the center of the lake seems to have been quite general prior to 1840. In that year, James D. Dana, the noted geologist, who was here with Commodore Wilke's Exploring Expedition, made an investigation of the lake.
>
> A series of levels were run from the ocean to the lake and Dr. Judd had a canoe carried over the rim of the crater and placed on its waters, from which soundings were taken. The level of the water in the lake at that time was found to be almost exactly that of half tide. The soundings showed no hole in the center and no depth greater than eighteen inches. Stakes placed at the water's edge showed that the lake was not subject to the tide.
>
> While a senior at Punahou in 1882, I became much interested in the problems connected with this lake. I made a number of trips on horseback to the crater and collected all the information I could from those familiar with the locality.
>
> In times of drought the lake would become almost dry (as evidently happened in 1853), and covered with a thick crust of salt. The salt from the lake was gathered up and stored in a large warehouse on the side nearest town. During rainy spells the lake filled up, only to dry up again when dry weather came. The source of the salt which was being removed continually in large quantities was not apparent.

[23a] Alexander, Arthur C., Actual facts as to Salt Lake, Honolulu Advertiser, August 9, 1926.

What interested me, however, as much as the increasing salt content of the water, was the well authenticated fact that the level of the lake was higher at the time of the spring tide than at any other time. There seemed to be only one explanation of the phenomena—a connection with the ocean above mean tide—that is above the normal level of the lake. Through such a connection sea water would flow into the lake at high tide, he amount being greater at the time of the spring tide than at any other. There being no outlet, the water would be held and evaporated by the sun, the lake being simply a big natural "salt pan."

I scrambled around the edge searching for such a connection. Fortunately it was a time of low water. I was rewarded finally by finding on the side toward Pearl Harbor a small stream of salt water oozing out of crevices a few inches above the surface of the lake and flowing into it. This explained all the phenomena and I reported the discovery to my geology teacher. His attitude, however, put such a damper on my enthusiasm that I could not muster courage to report it to anyone else.

From what is known of the behavior of the lake, it seems unlikely that a direct connection with the sea accounts entirely for its oscillations of level. It appears probable that fresh water springs, several of which were seen by Dana in 1840, have been effective agencies.

Before the introduction of water for the irrigation of sugar cane, it is probable that water rarely, if ever, stood over the bottom of Alaimanu, and that it was effectively drained by seepage into Salt Lake and westward toward Pearl Harbor. The same conditions probably existed in Makalapa. A few gulches having no permanent streams are developed on the tuff formations of the peninsula southwest of the craters. On the northeast, Moanalua stream, after a straight course down the slopes of the Koolau Range to within a half mile of the Aliamanu rim, turns abruptly to the south and flows behind the Salt Lake rim, reaching the sea at the apex of Kalihi Entrance. The two branches of Halawa stream, after pursuing similar courses on the range slope, join north of Aliamanu and turn westward to reach Pearl Harbor northwest of Makalapa.

DETAILED TOPOGRAPHY

The controlling, if not the most conspicuous topographic feature of the Salt Lake region is an extensive but much dissected sloping plain, which underlies the tuff in many parts of the area. From cursory examination it is known that this plain extends from the grounds of the Bishop Museum in Kalihi Valley, northwestward along the margin of the Koolau Range to Pearl Harbor. East of the Bishop Museum, this plain or terrace is less well developed. No detailed examination has been made of the corresponding area west of Pearl Harbor. The most striking remnant of the terrace is that on which the Fort Shafter military post is located, the whole of which will be designated in this paper as the Fort Shafter Terrace.

In the district from Bishop Museum to Fort Shafter, the terrace forms the present surface and extends from the eroded ends of the Koolau spurs toward the coast, merging seaward with uplifted coral plains and becoming increasingly cut by erosion. Its slope varies from 50 to 100 feet to the mile and its landward margin stands at 100 to 150 feet above sea level. In some places, principally adjacent to the larger streams, the terrace is composed of gravel. In other places it is cut at corresponding elevations on the basalt. Much of the Fort Shafter Terrace is obscured as a topographic feature by the pyroclastic craters and by the peripheral deposits of tuff which have been thrown out over its surface. Its gravels are exposed at various points in Moanalua and Halawa valleys in such manner as to show the configuration of pre-tuff topography and many of the details of the present configuration and structure of the tuff are most clearly explained with reference to it. The southwestern half of the Salt Lake peninsula from the line of the railroad to the coast is a low plain in most places less than 20 feet in elevation. A crescent-shaped area about three-fourths mile wide extending along the railroad on the landward side from Aiea nearly to Moanalua Gardens is slightly higher and more rugged, but formed in a similar manner by the mantling of thicker tuff deposits on remnants of the Fort Shafter Terrace. Nearly the whole rim of Makalapa and the southern portion of the rim of Salt Lake belong to this section. In the central area between the three craters and immediately west of Salt Lake, there is nearly a square mile of high land which rises in the cusp between Salt Lake and Aliamanu to over 360 feet. This land, sloping rapidly westward, was built up by the combined eruption of these craters. Deeply cut by a gulch, which drains into Salt Lake, it nevertheless presents an almost unbroken rim to Aliamanu. From the summit point of this central area a narrow rim about 150 feet in height extends northeast between Salt Lake and Aliamanu. This joins an irregular but more or less continuous rim crest which extends along the northeastern sides of the two craters and overlooks the lower Moanalua Valley. This latter ridge merges on the east with the lower and flatter-topped part of the Salt Lake rim and gradually rises westward reaching a maximum elevation of 485 feet in the high summit northeast of Aliamanu. The eastern portion of the rim forms a precipitous wall along one side of the gorge of the lower course of Moanalua stream, in which there is but one break for a distance of about a mile. At this point is a flat bottomed gap in the crater rim as seen from Salt Lake and which has been used as the route for the only road that enters the crater from the northeast.

The inner slopes of Salt Lake crater are in the main gentle, the only precipitous parts being those adjacent to the Aliamanu rim and to a short

cuspate spur which extends into the lake from the north, separating two of the apparent local centers of eruption.

From its summit point (485 feet) the rim of Aliamanu continues at lower elevations round to the west to join the high central area south of the crater, completing the circuit. The inner slopes of Aliamanu are much steeper than those of Salt Lake and adjacent to the two high points, rival the inner slopes of Diamond Head and other high craters. North of the Aliamanu rim is a soil-covered gap, where the tuff has been banked against the Koolau spur. This gap, known as Red Hill, stands at an elevation of about 300 feet. Approached from the southeast by a moderate grade, it overlooks the Halawa Valley at the northwest down a considerably steeper slope. Both the Moanalua stream and the Halawa stream in their swinging have cut in places steep bluffs against the sides of this tuff mantled extension of the Red Hill spur.

AREAL AND STRUCTURAL GEOLOGY

There are five principal formations in the Salt Lake district. The oldest of these is the Koolau basalt which is followed by the older parts of the reef limestone. Next younger is the Fort Shafter gravel. The oldest tuff of the region is next in age and appears to be contemporaneous with parts of the gravel. Included with the reef limestone in this classification are small amounts of marine calcareous sandstone and similar eolian sandstone. These are of various ages from pre-Fort Shafter to recent. The youngest distinct formation of the region is the younger tuff. The two tuff formations are so nearly coextensive in area that it is not practicable to give each a name derived from a type locality. They will therefore be designated as Lower Salt Lake tuff and Upper Salt Lake tuff (fig. 20).

The Koolau basalt forms the main mass of the range northeast of the Salt Lake peninsula. The spurs of the range are truncated along a line which runs southeast from Aiea toward Honolulu. At many re-entrants along this line and inland from it the basalt is overlain by the Fort Shafter gravel. (See Pl. IX, *A, C.*)

The principal outcrops of the Fort Shafter gravel are those in the west facing bluff which overlooks Moanalua Gardens and adjacent lowlands, the lower gorge of Moanalua stream, and the stream bluffs on either side of the lower Halawa stream. This formation is a coarse alluvial gravel. It is commonly made up of cobbles and boulders ranging from 10 to 40 cm. in diameter imbedded in a matrix of poorly sorted finer alluvium. The beds range from 2 to 10 feet in thickness and are distinguished chiefly by fairly sharp changes in the coarseness of the material. At a few places

are beds of fine alluvium with practically no pebbles. At other places are thick strata containing boulders from 75 cm. to 2 meters in diameter. Most of the boulders and cobbles have shapes which properly may be described as well rounded. This condition is not in harmony with the relative shortness of the streams which deposited the gravel, but is accountable by the general prevalence of spheroidal weathering. The boulders even at the heads

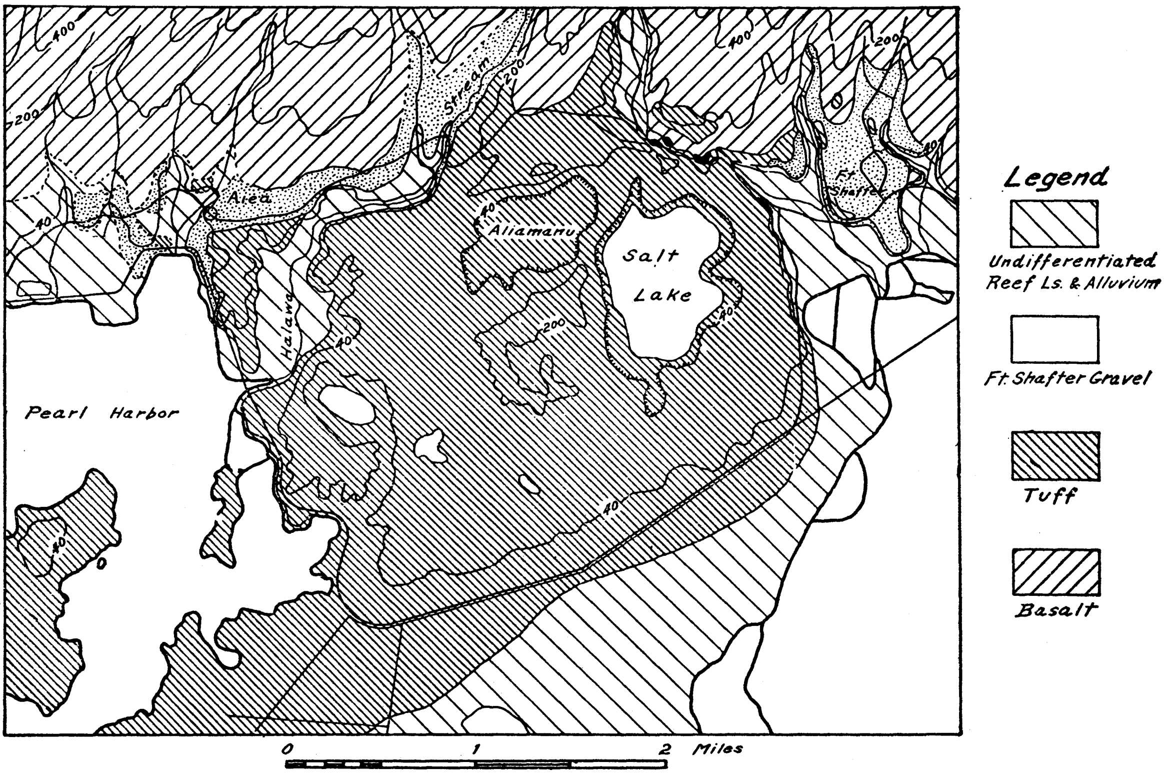


FIGURE 20.—Map showing areal geology of the Salt Lake district.

of the minor gulches in this region are commonly "well rounded" by spheroidal weathering. It is apparent here that the shapes of the cobbles and boulders in a stream are only to a minor degree the result of abrasion. Another factor to be considered is the generally weathered condition of much of the rock material in the streams. In many of the streams at the present time only a small fraction of the smaller cobbles and pebbles are composed of fresh hard basalt, whereas many of the larger boulders are weathered somewhat deeply. It is apparent that such abrasion as does take place will be much more rapid than that on fresh rock and the resulting forms will

be more the result of the configuration of the weathered zone than of the nature of the abrasive action. It seems that chemical weathering so largely predominates over physical weathering in this region that even the high gradient streams are able to secure relatively little fresh rock debris.

The Fort Shafter gravel is deeply weathered, containing practically no sound boulders. No quantitative data are at hand but the general appearance of the gravel at numerous outcrops gives opportunity for rough comparison with old alluvial gravels of various formations of the middle Atlantic slope of North America. The basaltic gravels of the Fort Shafter formation, though they are probably much younger, are more weathered, giving an appearance of greater age than the Potomac gravels of lower Cretaceous age of eastern North America. In fact, some outcrops of Fort Shafter gravel appear as old as exposures of the Triassic Newark formation. And when it is considered that the Fort Shafter gravel is of Pleistocene age, great rapidity of weathering in the Hawaiian region is apparent.

The extreme contrast between the conditions of gravel formations in the regions compared arises from the difference in the rock materials and method of weathering. The principal gravel formations of the Middle Atlantic slope of Tertiary and Quaternary age are highly quartzose; they are typical residual gravels of the continental type. On the other hand, the Oahu gravels are composed of the ordinary basalt, selected and culled of less resistant materials to a very slight extent. As compared with the Middle Atlantic slope, rock weathering by chemical processes is rapid in Hawaii.

The Fort Shafter gravel is the combined work of several streams draining this part of the Koolau Range, probably at a time when the sea stood about 40 feet higher than now. The inner margin of the Fort Shafter Terrace stands in places 125 feet or more above sea level but the slope of the terrace is such that this elevation is thought to be due to the normal rise of the grade landward from the mouths of the streams. Cut benches on which thin gravel deposits now lie in certain places at the Fort Shafter level are thought to be of fluvial origin and eroded in accordance with the higher established grades of the streams. These extensive gravel formations and high terraces which extend well into the valleys of several of the principal streams can hardly be attributed to tilting of the land, or with any greater plausibility to changes of level without uplift. With a land mass of so limited extent, neither of these conventional explanations seems satisfactory. The alternative interpretation, the only one which is apparently valid, involves a climatic change. On this assumption these gravel

fans were formed at a time when erosion and stream competence in the headwater sections of the valleys were greatly augmented by an increased rainfall. On the assumption that some correlation exists between island and continental climatic fluctuations, it seems likely that this increase of rainfall and augmented erosion was during one or more of the Pleistocene epochs when similar effects were produced in various extraglacial situations in continental areas. It is believed that increased stream competence in the headwater sections resulted in the delivery of excessive quantities of gravel to the lower sections of the valleys, which were thus aggraded deeply. The result was an increase in their channel gradients and corresponding increase in the capacity of the streams to transport the heavier loads reaching the lower courses.

The lowest (oldest) tuff of the Salt Lake region is found interbedded with the strata of the Fort Shafter gravels at a number of places. The exposures best showing this relationship are those in the bluff east of Moanalua Gardens, in the lower gorge of Moanalua stream and in the bluff east of the junction of the two branches of Halawa stream. The lower tuff not uncommonly occurs at more than one horizon in the gravel, and it is possible that there may have been two or more distinct epochs in its expulsion. Its occurrence in the gravel is so sporadic, however, and there are so few continuous thick beds of it that distinct subdivisions which could be correlated from place to place were not recognized, only the differentiation of the lower and perhaps complex tuff formation from the upper and simpler tuff unit of the last Salt Lake activity proving practicable. Even this separation is limited to structural criteria, since petrographic discrimination was impossible. It may be noted that all the exposures of the lower tuff in Moanalua and Halawa valleys are close to the margin of the Koolau Range and are situated at least 40 feet above sea level. Material identifiable as the lower tuff was found at lower elevations only along the railroad southwest of Aiea and at the northeast point of Fords Island. Here, the lower tuff is interbedded with fine sediments containing a few thin pebble bands. All the material seen was much weathered, the structure being obscure. But the fine grain of the sediments and the fact that they are overlain by coral reefs at 12 to 15 feet above sea level makes it probable that these beds were formed in an offshore position marginal to the main Fort Shafter Terrace.

The lower tuff is present as massive, air-deposited material at a number of places, but it nearly everywhere also occurs as stream-deposited tuff containing pebbles, and grades into gravels with tuffaceous matrices in which the volcanic element is recognizable only with careful scrutiny and with a knowledge of the surrounding structure.

The lower tuff was the result of one or more eruptions during the time of formation of the Fort Shafter Terrace. No evidence was found to determine with certainty whether the lower tuff came from all three of the known craters of the district or from only one or two of them. The distribution of the older tuff is essentially the same as that of the younger tuff, except that it has not been found in the seaward part of the areas, where it was probably deposited in the sea and was probably largely destroyed or obscured before the formation of the peninsula by the new tuff and coral reef. It seems reasonable to suppose, then, that the lower tuff is a product of the combined action of Salt Lake, Aliamanu, and Makalapa. The presence in the later tuff of Makalapa of fairly coarse grained fragments of an older tuff lend further validity to this view. The large quantities of lower tuff which were deposited on the terrace diverted the Moanalua stream and led to its present anomalous lower course. If the view be accepted that the Moanalua, in common with several other streams of this part of Oahu, pursued their lower courses over an extensive, sloping terrace, it will be clear that no very great amounts of ash were required to block its lower course. In all probability all the streams were dammed for a time, shortly resuming courses not far different from their former ones. The lower course of the Moanalua, however, was so effectively dammed that the stream was forced sharply against the margin of the Moanalua basalt spur, assuming a superposed course in which it has now become entrenched by cutting several notches in the basalt (Pl. IX, *D*). That this diversion and entrenchment took place in connection with the eruption of the lower rather than of the upper tuff is indicated by the fact that old gravel, which is almost certainly of Fort Shafter age, lies at the bottoms of at least two of these notches in the basalt. Since any gravel younger than the upper tuff would belong in and resemble a distinctly younger modern series, the old gravel in the notches may confidently be assigned to the Fort Shafter formation.

It may be that Moanalua stream was diverted in places to a third course by the deposition of the upper tuff, but distinctive evidence for such a diversion in addition to diversion following the first eruption is lacking. Nothing is known with certainty of the height and configuration of the craters of the early eruption. No masses of the lower tuff are known except those interbedded as parts of the Fort Shafter Terrace. The broad, low character of most parts of the modern craters suggests that most of the earlier craters had been destroyed by erosion and reduced to the level of the terrace. It is possible, however, that a small residual mass may have furnished the nucleus for the present northeast peak of Aliamanu.

The distribution of the upper tuff is indicated in figure 20. No means is known of discriminating between the tuff originating in the different craters. So far as known the later eruptions of all members of the Salt Lake group were simultaneous. The upper tuff is very similar to the lower tuff, variations in either from place to place being greater than the differences between the two at any one place. Over the Fort Shafter Terrace the upper tuff is from 1 to 5 feet thick and lies on the weathered and soil-covered surface of the Fort Shafter gravel (Pls. IX, *B* and X, *A*). The tuff is weathered at the surface and is readily identifiable only in fresh cuts in the margins of the terrace. This tuff is of the gray-black ash type, only slightly cemented. None of it shows a palagonitic character. This failure to develop into palagonite is rather common to those parts of the tuff which are dispersed in thin beds over areas some distance from the vents. The principal mass of tuff surrounding Salt Lake is mainly of the palagonitic variety. Local variations may be due to topographic position, or may be merely apparent variations due to the type of exposure. In the lower and marginal parts of this area the tuff is a compact buff to purplish colored rock containing a few small bombs. In the thicker parts of the northeast rim where the upper tuff is cut by a recently constructed road it is a strikingly vari-colored rock containing numerous fragments of basalt, reef rock, lower tuff, and a few crystals of olivine and augite. On the top and inner margin of the northeast rim and higher parts of the north and west rims, the tuff is a rough weathered, dark gray, or brown rock, on the surface of which are numerous large bombs and basalt blocks. The largest mass of basalt seen in any tuff on Oahu rests on the surface of the Salt Lake tuff on the spur southeast of the north point of the lake. Its dimensions are 2.5 by 2 by 2 meters; and its estimated weight about 20 tons. Large and small fragments of basalt, most of them probably bombs, are very numerous on the inner rim of Salt Lake basin. In this weathered gray tuff augite fragments and bombs of granular olivine as much as 10 cm. in diameter are found in considerable numbers. Except on the southeast side, reef rock fragments are not numerous. The upper tuff of Makalapa is mainly a buff, mottled, palagonite tuff. The bombs within it are more numerous near the crater. Faint bands of cross-bedded tuff on the northeast rim of the crater appear to be the result of wind scouring and deposition soon after the eruption. In a few places, the younger Makalapa tuff contains fragments of older tuff presumately from the same crater.

It is very difficult to avoid false impressions of the character of the tuff derived from the surface forms and colors developed by weathering. It is probable that the tuff is more homogeneous than its variously weathered and eroded outcrops appear to indicate. The tuff of the Salt Lake region

may be described in a broad way as containing more coarse material, larger olivine and augite masses, and as being thereby more mottled in appearance and inclining more to gray, purple, and drab colors than the other tuffs of Oahu.

The beds on the low south rim of the lake basin are nearly horizontal over a zone several hundred feet wide and in few places reach talus angles. The upper tuff was banked against the Moanalua and Red Hill spurs, filling in the valley of the Moanalua to over 200 feet above sea level. It appears that the stream resumed its former entrenched course with only minor changes. That there were some minor changes is indicated by the fact that tuff, gravel, and basalt alternate in the walls of the present Moanalua gorge and that there is at least one place where tuff is now bedded across what appears to have been a former notch cut through the basalt. At the point where a road now crosses the rim from the gorge to the Salt Lake basin, the low gap is a result of the sharp southwestward swinging of the present valley. The stream has here cut away a segment of the crater rim, leaving the flat topped remnants of the crest on either side. The lower portion of the Moanalua golf course is located on the recent flood plain of the stream. The upper portion of the course is laid out on a tuff mantled gravel remnant of the Fort Shafter Terrace, which is here nearly 200 feet high.

Commonly, the upper tuff lies unconformably on weathered and soil covered gravel. Tree trunk casts in the upper tuff show that the surface was covered with vegetation. Erosional unconformity, while found at certain localities, is not pronounced in most exposures.

Around the margins of the tuff covered area, along the road south of Moanalua Gardens, along the shore south of Aiea, and at various places in Pearl Harbor, the upper tuff is mantled over low cliffs. In some places this results in a monoclinal structure a few yards wide, by which the tuff dips from a higher level on the cliff to a lower one at its foot. In other places the tuff was thrown down in blocks and tumbled about even before the cessation of the deposition. This talus material is incorporated in a calcareous matrix and some of it is associated with coral fragments. At still other places, a later reef formation lies on the lower part of the tuff. These various monoclinal structures lie between the present sea level and about 15 feet above and the field observations indicate that the upper tuff was deposited when the sea stood 10 to 12 feet higher than now, and that this relation was maintained for a considerable period following the eruption. The monoclinal structures represent mantling of the tuff over low sea cliffs at certain places and over the edges of reefs at other places. Apparently wave action attacked the new formation at once,

for the cliff breccia at certain localities appears to be essentially contemporaneous with the layers of tuff. Probably much of the land area southwest of the railroad dates from this eruption, when the reef of this section was so mantled with tuff that its growth ceased.

SUMMARY OF GEOLOGIC HISTORY

Some time after the Koolau Range had been cut back to the line of cliffs which now extends from Makapuu Head to Pearl Harbor at the inland margin of the coastal plain, fluvial action became more vigorous, a series of coalescing gravel fans being built along the margin of the range. In the vicinity of Salt Lake, these fans were one to two miles long and added a considerable area to the island. During the formation of these fans one or more of the Salt Lake craters was in eruption. The resulting pyroclastic materials were spread as widely as those of later date and were also extensively incorporated in the gravel deposits. The materials from this eruption filled the channel of Moanalua stream and forced it sharply against the margin of the range, causing it to become fixed in a course reaching the sea at least two miles to the east of its original mouth. It is not known precisely how far to the southwest the tuff from the first eruption extended in thicknesses sufficient to materially build up the sea bottom. It appears possible that the tuff may have been a factor in helping to start the growth of corals and the formation of a reef which is the basis of broad areas of land both east and west of the entrance to Pearl Harbor. Little is known of the history of the district in the period following the first eruption. It is believed, however, that the greater part of the tuff, which in the several craters had stood above the surface of the terrace, was cut away by lateral swinging of the streams before the second eruption occurred. The position of the upper tuff on coral reef at all the known seaward locations indicates that coral growth had extended seaward at least as far as the present land margin before that event. It seems probable that this growth of corals was mainly in the period after the vigor of the fan building streams had been diminished and the influx of terrigenous material reduced.

Relative to the land, the sea had become lower by about 25 feet and stood at a level only about 10 or 12 feet higher than now, at the time of the second and last eruption. The ash from this eruption probably considerably extended the land area both directly by filling to above sea level and also by under water filling of broader areas, where plants could take root and ultimately promote land building. With the eruption of the upper tuff, the present topography was blocked out. The valleys of Moanalua

and Halawa streams were again filled to depths of a hundred feet or more, but were re-excavated with only minor changes in their courses. The cutting in these valleys and that along the coast constitute the only considerable amount of modification of the tuff deposits. A small amount of erosion of the lower parts of the craters has taken place. The higher peaks have been reduced by some scores of feet, while the broad outlines of the topography are essentially those established by the deposition of the tuff.

Since the second eruption, the land has risen relative to the sea by about 10 or 12 feet and assumed its present position.

TANTALUS CRATERS

LOCATION, FORM, AND SIZE

The late volcanic features included in the Tantalus group of craters are the pyroclastic craters of Tantalus, Sugarloaf, and Roundtop and the rhyoclastic crater, Rocky Hill, with its associated dike flows and ejectamenta. Tantalus crater is located on the Pauoa-Manoa range spur about two miles southwest of the Koolau crest and four miles inland from the waterfront in Honolulu. (See map, fig. 5.) Sugarloaf is one and one-fourth miles nearer the sea on the Makiki-Manoa branch of the same spur, and Roundtop lies on a continuation of this line six-tenths mile beyond. Rocky Hill is a separate elevation standing at the west side of the entrance to Manoa Valley and in direct line with Tantalus, Sugarloaf, and Roundtop. Extending along the west side of Manoa Valley from the Mills School inland, is a line of low rocky knobs which are composed of materials closely resembling those of Rocky Hill and which are believed to be of contemporaneous origin. The Tantalus group is the only series of craters in which only one period of activity was recognized.

Mount Tantalus (Puu Ohia) consists of three peaks which rise to the north, east, and southwest respectively of a central depression. Two of the peaks reach 2,000 feet, the third is over 1,960 feet above sea level. In the central depression, an area of about four acres lies below 1,840 feet and of the whole crater, including the three peaks and the basin, approximately one-eighth square mile is included within the 1,800 foot contour. Sugarloaf is a low mound about 200 yards in diameter which rises about 100 feet above the adjacent ridge. Its summit reaches 1,440 feet above sea level. The oval cone of the Roundtop mass is a half mile wide and a mile long, and its summit reaches 1,080 feet. Sugarloaf and Roundtop lack distinct craters. Northeast of Sugarloaf is a low depression, which is probably the

site of the vent; and at the northeast margin of the higher part of Roundtop are coarse pyroclastic materials with some flow lava, which indicate proximity of a vent although its exact location is unknown.

Rocky Hill is a sub-circular mound, one-fourth mile in diameter and about 125 feet high. None of the several low mounds extending in a line northeastward up Manoa Valley is more than 400 feet long and 60 feet high.

DETAILED TOPOGRAPHY

The topography of the craters of the Tantalus group differs from that of the other groups of Oahu craters in that it is superposed on the topography of the Koolau Range. It is therefore less conspicuous in itself and consists chiefly in certain modifications of the normal range topography. Tantalus stands on the spur between Pauoa and Manoa valleys. The heads of these two valleys are incurved toward each other and a very unusual flat area, known as Pauoa Flats, forms the divide between the streams. Pauoa stream has a distinctly abnormal profile, consisting of a low gradient lower portion, a steeper middle portion, and a gentler head portion which drains Pauoa Flats. On the southeast side, Pauoa Flats is limited abruptly by the precipitous head wall of Manoa Valley. From the north summit of Tantalus eastward into Manoa Valley, the descent is 1,200 feet in four-tenths mile. To the west and northwest, the slopes to Pauoa Valley, though steep, are less precipitous.

Southwest of Tantalus, the spur splits into two branches inclosing Makiki Valley. Into the head of Makiki Valley from Tantalus is a slope of 800 feet in one-third mile. Sugarloaf and Roundtop are situated on the easterly branch of the spur. The Manoa slope of this spur is generally steep and broken by only minor re-entrants. The ash mantled part of this slope adjacent to Roundtop has a grade of about 1,000 feet in a half mile. The basalt cliff northeastward from Sugarloaf slopes generally at twice this rate. Makiki Valley is cut less deeply than either Manoa or Pauoa valleys and the Makiki slope of the Roundtop spur is less precipitous and less regular than the Manoa slope. That part of the spur which lies east, south, and west of the summit of Roundtop consists of smooth, concave, ash-mantled slopes.

The Makiki-Pauoa spur is narrower than the Roundtop spurs and toward its foot develops two branches. The eastern branch, which is followed by the road, is composed largely of ash; the western is part of the original basalt spur eastward from Pauoa.

AREAL AND STRUCTURAL GEOLOGY

Two rock formations besides the Koolau basalt can be distinguished in the Tantalus district. These are the black ash and associated agglomerate and the Rocky Hill agglomerate-rhyoclastic series (fig. 21). The black ash covers the surface of a considerable area in the vicinity of Tantalus and extends down the crests of the two branches of the Tantalus spur. Near the lower parts of these, the ash widens out and forms a continuous

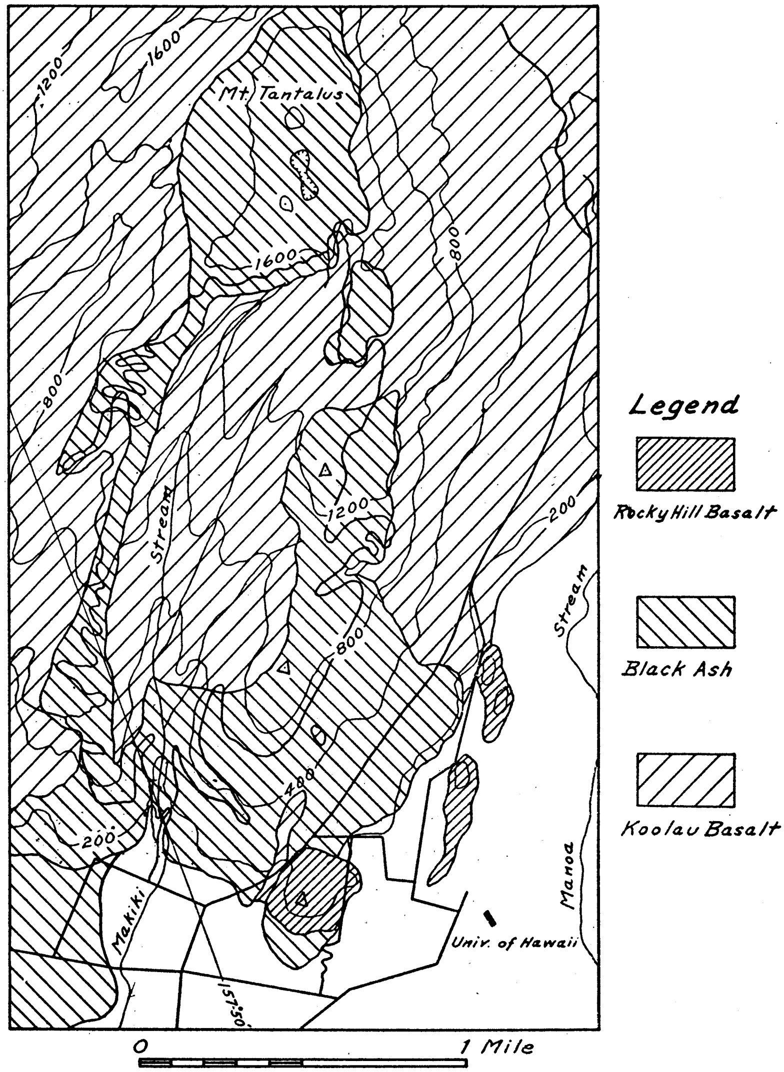


FIGURE 21.—Map showing areal geology of the Tantalus-Roundtop district.

zone a half mile wide extending from the southeast flank of Roundtop to Punchbowl. There is no doubt that the ash originally covered all the upper Makiki Valley, having been removed by erosion.

No means is known of distinguishing the ash from the three craters, Tantalus, Sugarloaf, and Roundtop. The black ash of this group of craters is less well exposed than the tuff of some of the other groups. Its structure has not been studied in such detail. However, from the exposures along the trails and roads, it appears that pre-existing topography so largely controlled the configuration of the newly deposited ash that the dips of the beds are nearly everywhere down the slopes of older elevations and parallel to the present general surface. Near the summits of Tantalus, Sugarloaf, and Roundtop the structures are characterized by maximum talus slopes with shifting strikes, indicative of very rapid accumulation.

The bulk of the material resulting from the eruptions of Tantalus, Sugarloaf, and Roundtop is black ash composed of vesicular twisted and ropy particles of black, basaltic glass ranging from 1 to 10 mm. in diameter (Pl. X, *B*). Smaller amounts of coarser agglomerate made up of bombs, ranging up to 10 cm. are found near the vents. The bombs are commonly rudely spheroidal and stony, rather than glassy in the interior, cooling having been slower in these larger pieces. Along the Roundtop Road are good exposures of agglomerate grading into rhyoclastic material and of small masses of flow lava, indicating that at least a small amount of liquid lava flowed to the surface in the Roundtop eruption. (See Pl. X, *D*.) In the deeper parts of some of the cuts the black ash is compactly cemented, but in only one place does any alteration to true tuff appear. On the west slope of Tantalus about 300 feet below the summit and in a fresh cut along a trail, are a few thin beds of a dark, purple drab tuff in which the remnants of a few black glass lapilli were embedded in a matrix of dark palagonitic material.

Rocky Hill and the several small mounds which lie along the line of a dike to the east are made up in part of coarse ash and agglomerate and in part of rhyoclastic lava. The structure of the lava indicates extrusion in an extremely viscous condition. The successive masses lie on one another at high angles and all show strong flow structure. Material of this sort grades into masses made up of ropy and nodular lumps which have fused together after accumulation, and these in turn into deposits of detrital agglomerate and ash.

SUMMARY OF GEOLOGIC HISTORY

The eruption of the craters of the Tantalus group is believed to have taken place at a much more recent date than that of the first activity of Diamond Head and Punchbowl. It seems probable that the Tantalus activity was synchronous with the later, black ash eruption of Punchbowl. The Tantalus eruption commenced with expulsion of black ash from the higher craters, its closing stages marked by the expulsion of coarser agglomerate and rhyoclastic material, to a slight extent, from Sugarloaf and Roundtop, but more particularly from Rocky Hill and the Manoa dike.

KOKO CRATERS

FORM AND SIZE OF CRATERS

This Koko group of craters is the most important series of late volcanic features on Oahu. It includes the largest number of different vents and presents the most complicated and instructive history of all the pyroclastic districts. The group extends along a northeast-southwest line a distance of six miles from Koko Head to Manana Island. Koko Head and Koko Crater with the intervening Hanauma Bay are prominent and well known features. Manana Island (Rabbit Island), Kaohikaipu Island, Kalama crater,[24] Kahaulou crater, Ihiihilauakea crater, and Nonoula crater as well as several vents along the Koko dike,[24] are less well known. (See fig. 22 and Pl. XI.)

Koko Head is a rounded tuff dome about a mile long in a north-south direction with a relatively flat summit about three-fourths mile wide. Combined with the lower promontory southeast of Hanauma Bay, it forms a peninsula slightly more than a mile wide. The highest point is 644 feet above sea level and an area of about 25 acres is above the 600 foot level. Koko Head is probably the western part of a crater rim which was never symmetrical nor much more complete than now.

Hanauma Bay is a pronounced re-entrant in the Koko peninsula, slightly wider at the inland end than at its mouth. It is bordered on three sides by a well developed and somewhat complex crater rim. (See Pl. XII.)

A half mile northeast of Hanauma Bay is the small Kahaulou crater, nearly circular in outline and about 300 yards across. Its northwest rim is 75 to 100 feet high, and a similar but lower rim forms the southeast border. Its southwest side is a mound rising about 200 feet above the crater bottom and presenting a steep wall toward the bowl. On its north-

[24] In the absence of local names for the features indicated, the terms Kalama crater and Koko dike have been adopted.

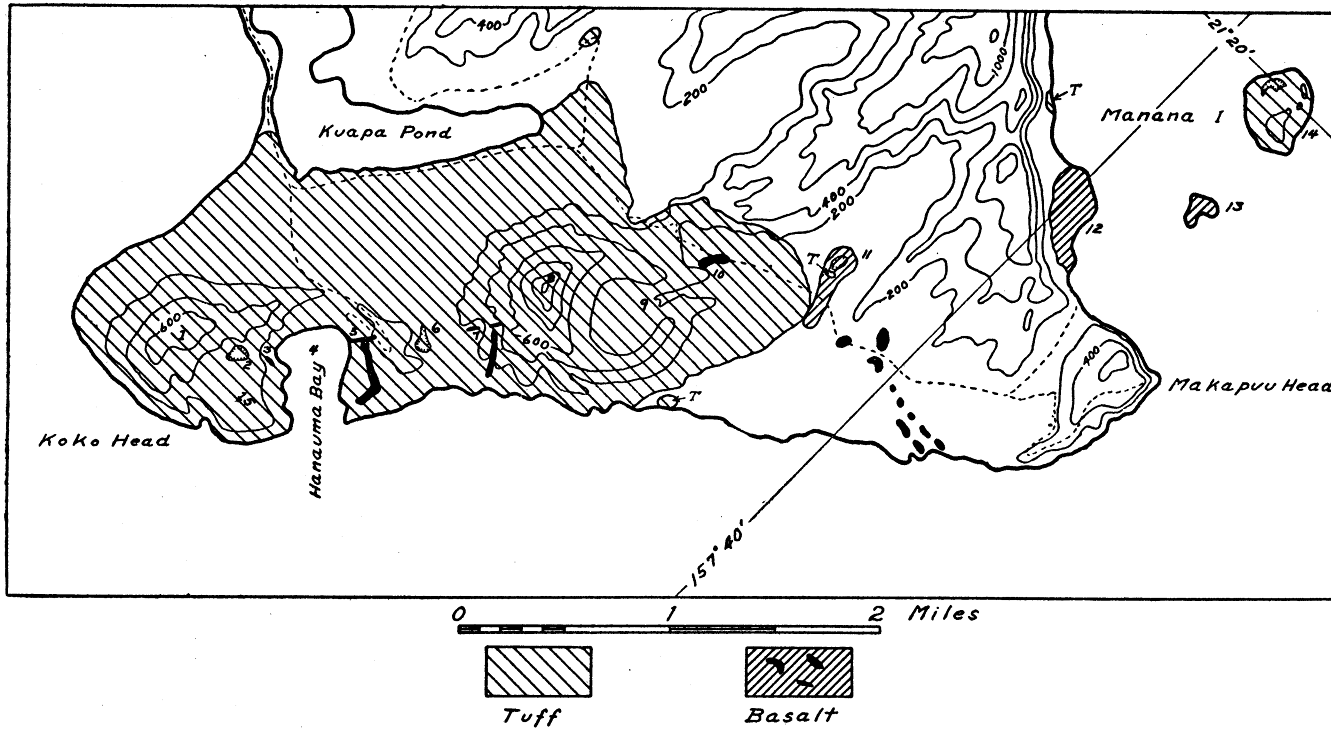


FIGURE 22.—Map showing areal geology of Koko district: 1, Koko Head summit; 2, Nonoula explosion crater; 3, Koko dike; 4, Hanauma Bay; 5, Koko dike; 6, Kahaulou explosion crater; 7, Koko dike; 8, Koko Crater summit; 9, Koko Crater vent; 10, Koko dike; 11, Kalama crater; 12, Koko dike shore flow; 13, Kaohikaipu Island flow; 14, Manana Island; 15, Ihiihilauakea.

east side the rim is considerably dissected by large gullies which head high up on the adjoining Koko Crater. As a result of this drainage the bottom of Kahaulou slopes with a considerable gradient toward the southwest, consisting of alluvial fill probably some scores of feet in thickness.

Koko Crater is the highest and in many ways the most impressive pyroclastic crater on Oahu. Its base covers a nearly circular area about one and one-fourth miles in diameter, extending entirely across the Koko peninsula from the sea to Kuapa Pond (fig. 22). The crest of the rim forms an eccentric circle about a half mile in diameter (Pls. I and XIII, *B*), broken by a gap on the northeast side through which the crater is drained. The height of Koko Crater varies from about 500 feet on the north, east, and south sides to 1,205 feet at the southwest side, where the tuff was driven by the trade winds to form a magnificent crescentic cone. At this point, the width of the rim at the base is about three-fourths mile; whereas the rim on the opposite side has a base width less than a third as great (Pl. XIII, *A*).

Kalama crater, standing in the bottom of Kalama Valley, and slightly nearer the east side, is roughly circular in outline and measures about 750 feet across the rim. Its bowl, which is undrained, is about 50 feet deep. From the crater a low ridge of lava extends southward.

Manana Island has an average diameter of about 2,000 feet and rises to a height of nearly 400 feet. More than two-thirds of its area is above 100 feet and there is practically no flat land near the sea. Kaohikaipu Island is a low rock of about 6 acres which rises 50 to 60 feet above the sea.

DETAILED TOPOGRAPHY

The most conspicuous feature of Koko Head as seen from the west, is the flatness of its summit and the smooth, rounded outlines of its elongate mass. At the north it is connected with Koko Crater by a low ridge, sloping at the south with increasing steepness to the sea. Closer inspection, however, shows the west face of Koko Head to be trenched by numerous consequent gullies similar to those of other craters and reaching depths of 50 to 100 feet on the steeper parts of the slope, and 5 to 10 feet across the gentler slopes near the sea. Adjacent to the triangular area of flat land northwest of Koko Head, the shore of Maunalua Bay consists of a sand beach. Along the flanks of the crater the sand beach gives way gradually southward to a low cliff cut in tuff which in turn changes to higher cliffs. Near Kawaihoa Point marine erosion is so much more rapid than fluvial that the gullies are miniature hanging valleys, which enter the sea by a series of falls many of which are impassable to climbers without ropes.

The south face of Koko Head is precipitous. It is bordered by vertical sea cliffs, 100 to 200 feet high, above which the ground rises at angles of 60 or 70 degrees and at about 500 feet above sea level gives way to the normal slope of the crater flank. Only one other pyroclastic crater, Ulupau Head, has been so deeply eroded or presents so bold a cliff on the ocean side.

The southeast side of Koko Head is cut by a single deep gulch about 1,500 feet long. Between this gulch and Hanauma Bay is a triangular area of land, which is a little more than 200 feet in elevation. At the seaward margin of this area is a curving ridge of 40 to 50 feet high, and inland from this ridge is a low basin. Still farther inland is the deep undrained crater of Nonoula. Koko Head overlooks this triangular area with steep slopes which become precipitous west of Nonoula and continue northeastward as the inner slope of the rim, which swings round Hanauma Bay from the north end of the head. From the south face of Koko Head around the triangular platform to the head of Hanauma Bay, is a continuous sea cliff 50 to 200 feet high.

A complicated rim connects Koko Head with Koko Crater round the head of Hanauma Bay (Pls. XI and XIV, *C*). From its crest northwestward, slopes are smooth in longitudinal profile and are cut by a few shallow gullies. Southeast of its crest a short slope leads down to a flat bench which extends to the edge of the cliff forming the actual margin of the bay. This bench in places is highest at the edge and has a definite back slope, which becomes more pronounced toward the east. Here the sag between the back slope and the main rim slope is continuous, through a low col, with the head of a small valley which runs parallel with the east shore of Hanauma Bay and enters it near the main coast line. The principal rim round the head of Hanauma Bay terminates northwest of the valley in the high mound on the leeward side of Kahaulou Crater. Round the two sides of Kahaulou, lower rims pass from this mound to join the steep flanks of Koko Crater. On the west and southwest sides the in-facing slopes of Kahaulou are precipitous and in places overhanging.

The outside slopes of Koko Crater are deeply scored with radial gulches similar to but larger than those of the other high craters of Oahu. An exception is found on the southeast side where a valley of considerable size follows a tangential course behind a shore ridge for about a third of a mile. A few gulches of moderate depth are confluent inside the crater and form the gulch by which the bowl is drained through a narrow breach toward the northeast. For the most part the steep slopes of the interior are less scored by channels than are the outer slopes. Much of the crest of the crater rim is of the knife-edge sort. It may be traversed only with great care. On the

south slope of the crater, one of the narrow spurs is pierced to form a natural arch about 40 feet wide on a 30 degree angle and about 7 feet high. A continuous sea cliff extends along the shore from the head of Hanauma Bay to a point east of Koko Crater where it gives way to sand beaches along the margin of the low plain. Along this shore are remnants of an uplifted marine bench 10 to 12 feet above sea level. From the inner margin of this bench the cliffs rise to heights of 10 to 150 feet.

The inside of Kalama crater is strewn with blocks of basalt. Similar blocks are found less thickly strewn on the outside of the rim and on the surface of the low mass of lava which extends south from it.

Manana Island (Rabbit Island) is a doublet formed by two crater vents, one at the northwest side, within a topographic depression and the other on the east side (Pl. XIV, *B*). The rim of the northwest crater is still largely intact but that of the east crater is largely cut away by marine abrasion. The highest part of the island (360 feet) lies southwest of the east vent; on the southeast and east it presents sea cliffs more than 100 feet high; gullies of moderate size appear on its west and northeast sides. The north and northeast coast of Manana is wave cut, the rim of the northwest crater now standing as a cliff 200 feet high. The remainder of the crater is little modified from its original form. Kaohikaipu Island, as seen from the summit of Manana, appears to be a lava island mantled with banks of red soil possibly formed from Manana tuff by weathering.

AREAL AND STRUCTURAL GEOLOGY

Four principal rock formations are found in the Koko district. In order of age, these are Koolau basalt, the oldest tuff, basalt of Koko dike and Kalama crater, late Koko tuffs, and modern alluvium. Certain parts of the tuff are nearly if not quite as recent as any of the dike lava. (See p. 82.) Small remnants of reef rock are found beneath the tuff at a few places.

Because separate mapping of the tuffs of different ages has not proven feasible, their structures are described chiefly by areas. The tuff of the Koko district varies from the ashy type which has been altered from black ash to dense semivitreous reddish-brown tuff consisting almost wholly of palagonite. In certain parts of the Koko region deposits of black ash 5 to 10 feet thick lie just beneath the surface, evidently the product of eruptions which elsewhere have produced palagonite tuff.

The structure of the tuff, so far as it is revealed in exposures, is shown in figure 23. The position of most of the beds which dip either way from the crests is of little significance except as emphasizing the deposition of the tuff as a mantling of pre-existing ridges. In many places the structure

of the tuff is doubtless similar to the structure of the original beds of the rim (Pl. XIV, *A*).

The lower land adjacent to the northwest flank of Koko Head and continuing northeast to the lower flanks of Koko Crater is mantled with black ash, the upper part of which has weathered to a deep red soil. This ash appears to have come from the last eruption of Koko Crater. The curving rim extending around Hanauma Bay is mantled with tuff which is characterized by the presence of unusual quantities of reef rock. (See

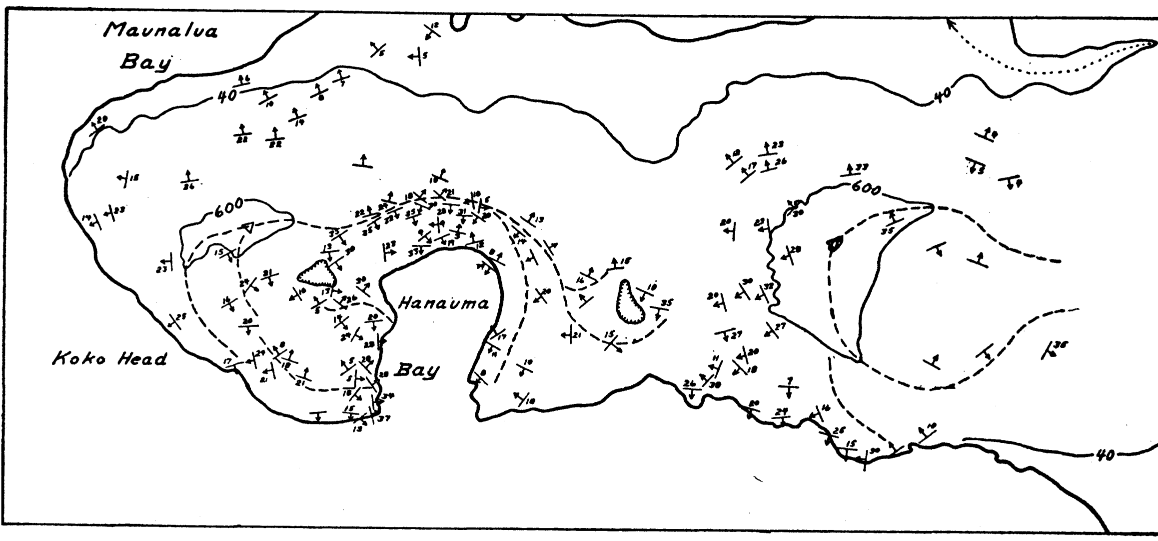


FIGURE 23.—Structure map of Koko region.

Pls. XV, *A*; XVI, *B*, *C*.) At its eastern limit this tuff is clearly the product of an eruption from Kahaulou crater which occurred later than the Koko Crater eruption. On the higher parts of the south end of Koko Head and extending eastward is a mantle of deeply weathered tuff which becomes thicker to the east and is conspicuous for the great number of included basalt bombs (Pl. XVI, *C*), most of which show polygonal cracking on one side parallel with a laminated structure and a ropy or honeycombed form on the other. The bombs appear to have been blown out as fragments of a crust on a lava pit. This material is believed to have come from Nonoula (Pl. XV, *B*). With these exceptions, the main mass of Koko Head appears to be a unit and the product of a single eruption. The subdued topography suggests that it may be one of the oldest craters on Oahu—a view supported by the fact that it is difficult to locate the vent from which the material came. The crater Nonoula is too far to the north and is quite too fresh

to have been the source of the material of the main head. So far as can be discerned from the curve of the crest, it seems likely that the Koko Head vent is beneath a considerable thickness of subsequent tuff in the vicinity of Ihiihilauakea, where the structure of the tuff is very irregular. But this irregularity is the result of mantling an irregular topography and affords therefore no evidence for or against this location of the vent of Koko Head. It is, however, reasonable to suppose that wave erosion of the east part of the original crater would largely destroy the rim and furnish a somewhat rugged foundation for subsequent deposition of tuff.

Three tuff formations are found in the Hanauma Bay district. In the extreme head of the bay a younger tuff which forms the sea cliff round the bay is seen to overlie an older one with pronounced unconformity. The older tuff is believed to be that of the outer rim which runs from the flanks of Koko Head to the high mound west of Kahaulou. Although similar relations are found at places on the west shore of the bay, it is uncertain that the same formations are involved. On the basis of composition it is difficult to distinguish one tuff from another. Furthermore local channel unconformities found between beds differing in age by only a few days or weeks are difficult to distinguish from those having more time significance. These are especially abundant along the coast where wave erosion must have commenced immediately after eruption and where the stream channels were cut most deeply.

From the head of Hanauma Bay eastward around the east point, a third tuff formation is seen to lie unconformably on the second. On the east shore of the bay the earlier tuff is nearly horizontal, the later one mantled at the angle of rest over an earlier sea cliff. This latest tuff appears to be that of the late eruption of Kahaulou. Associated with it and likewise spilling down over the sea cliff near the extreme north point of the bay is a small lava flow from Koko dike. Exposures of lava from this dike are also found to the northeast on both sides of the small valley which reaches the coast at the east point of the bay. In this valley, lava which came from Koko dike flowed down the sag in newly deposited ash of the late Kahaulou eruption and reached the sea in very small quantities. It appears that this dike was in eruption just at the close of the Kahaulou activity and represents the final volcanic episode in the Koko district and probably on Oahu. A similar thin lens of basalt is found in the reentrant above Hanauma Bay and northeast of Nonoula (Pl. XVII, *B*).

Hanauma Bay was the center of two eruptions, one producing the outer rim and the other the smaller rim which now forms much of the sea cliff. The first eruption of Hanauma crater was probably nearly or quite contemporaneous with the first Koko Head activity, the rims of the two

craters merging southwest of the present site of the bay. It seems probable that the southeast rim of Hanauma was complete and was later cut through by the waves. The second eruption of Hanauma crater took place before either the Kahaulou or the Nonoula eruptions and in addition to forming a smaller crater rim round the bay threw large quantities of tuff into the eroded crater of Ihiihilauakea from which Koko Head may have come. Subsequently Nonoula added to this fill.

There is no evidence that Kahaulou was in eruption more than once. The tuff from this crater contains notable amounts of reef rock and calcareous sandstone and the eruption clearly took place with great violence through an old reef. Blocks of reef rock a meter in diameter are not uncommon at points 200 feet above sea level on the southwest rim. The greatest mass of Kahaulou tuff lies in the high mound on the southwest which was built over a part of the earlier outer rim of Hanauma crater. This tuff is mantled a small distance up on the nearby flanks of Koko Crater and lies generally over the area to the southwest as far as the opposite shore of Hanauma Bay. Its greatest thickness is about 25 feet.

Aside from a small amount of Kahaulou tuff on its lower south flanks only one tuff formation is exposed in Koko Crater. This is the great mass of moderately coarse palagonitic tuff which forms the strongly eccentric rim, probably the largest unit mass on Oahu. Though the outer layers are ashy in many places, everywhere a few feet below the tuff is altered to palagonite and in the interor of the mass in some of the deep gulches is found the most completely indurated tuff noted anywhere on the island. On the south side of the crater is a spur which projects to the east. On the north side of this spur are northward dipping beds. A valley is developed in a synclinal structure of depositional origin. No older rock mass was identified as the nucleus of this mantled ridge and all the tuff exposed appears to belong to the same formation as that of the main crater. It is clear, however, that some mass of elevated land existed here before the deposition of the Koko Crater tuff. Since this site is well outside the line of the Waialae cliffs of the Koolau Range, which were the coast line before the beginning of pyroclastic action, it seems probable that this nuclear mass was the remnant of a crater formed contemporaneously with the earlier Hanauma and Ihiihilauakea eruptions.

Most of the tuff of Koko Crater was thrown out on a surface, which was smooth and free from any considerable irregularities and probably in part under water (Pl. XVII, *A*). It was apparently erupted at a time when the trade winds were of unusual strength for it is the most pronouncedly asymmetric crater on Oahu.

At the road gap to the north of Koko Crater, tuff lies on Koolau basalt, and the basalt several feet thick appears at a number of places to the east and north of the road. A small patch of tuff presumably from Koko Crater lies at the south summit of the rim of Kalama crater on the basalt.

Kalama crater, so far as known, was in eruption but once and its activity must have antedated at least the later stages of the Koko Crater eruption. The lava from Kalama flowed toward the sea.

The tuffs from the two vents on Manana Island were not distinguishable in the field. Two types of tuff, gray and buff, found as beach pebbles on the southwest shore appear to be only different phases of original composition and alteration. The rim of the northwest crater is complete and the structural crest does not depart greatly from the topographic rim. On the northeast the outdipping beds have been largely cut away by the sea and the structural crest is at or beyond the brink of the seacliff. While the east crater merges with the northwest crater, no evidence of different age was seen and it is believed that they were formed nearly simultaneously. The structural center of the east crater is exposed in the surface of the broad wave cut bench on the east shore of the island. The bench was apparently determined by the lesser resistance encountered by the waves in the lower center of the crater saucer. The tuff beds have tangential strikes and infacing dips round a center which is nearly at the center of the bench remnant.

SUMMARY OF GEOLOGIC HISTORY

Much of the pyroclastic activity in the Koko district took place while the sea level was about 12 feet higher than its present position. The first activity consisted of eruptions of Ihiihilauakea, Hanauma, and the unknown center from which the land mass south of Koko Crater is thought to have come. The main mass of Koko Head and the outer rim of Hanauma Bay date from this time. At a considerably later date and after extensive erosion of these masses, Hanauma crater and Koko Crater became active, when the inner rim of the bay and the high crater were formed. It is not known whether or not these were active simultaneously. Before the close of Koko Crater activity Kalama crater was formed and its lava poured out on the plain to the south which had evidently been built around the craters of the first eruption. After the rim of Hanauma Bay had been eroded away on the southeast, probably for the second time, the eruptions of Kahaulou and Nonoula, and the lava flows from Koko dike at five different points between Hanauma Bay and Koko Crater completed the history of volcanic activity in the mainland Koko district. The relative dates of the Manana Island

and the Kaohikaipu Island eruptions is not known with certainty. The presence of Manana Island tuff overlying old soil, which in turn overlies old reef formations on the mainland opposite Manana, indicates that the eruption took place after the emergence of Oahu from the lowest (40-foot) position. Moreover, though the wave erosion of Manana is considerable, it is impossible to believe that it has been exposed to wave erosion longer than the newer Koko Crater and Hanauma Bay tuff formations. The Manana eruption is therefore thought to have been nearly or quite contemporaneous with the later Koko series. These events had all taken place before the shift of sea level which left the marine bench extensively exposed about 10 or 12 feet above mean tide.

ULUPAU CRATERS

LOCATION, FORM, AND SIZE

The Ulupau group of late volcanic features include the tuff crater of Ulupau Head, the tuff island of Moku Manu, and the ash and lava crater Puu Hawaiiloa. These features are the nuclei around which coral reefs have grown and wind built dunes have formed to make the seaward half of the Mokapu Peninsula. (See fig. 5.)

Ulupau Head consists of a crescentic remnant of a tuff crater about three-fourths mile long in a north-south direction and about a half mile wide (Pl. XVIII, *A*). A semi-detached remnant of the same crater lies to the east and together the two form an elevated area of a mile in width. The summit of the main mass is over 680 feet above sea level. Puu Hawaiiloa is a rather steep cone a half mile in base diameter and about 300 feet high, from the north side of which a low sprawling ridge of late lava extends north to the shore and westerly along the shore for about a mile. Moku Manu is the name applied to a pair of rocky islands which lie about a mile north of the extreme northeast point of Ulupau Head. They have a combined area of approximately 20 acres, the higher of the two reaches 200 feet above sea level.

DETAILED TOPOGRAPHY

The seaward part of Mokapu Peninsula may be described as consisting of two horns, pointing northeast and northwest, respectively, with a curving coastline of about two miles in length between them. (See fig. 24.) Five principal divisions may be recognized in the topography of the area: the higher parts of Ulupau Head, the flanking slopes of the head, the slopes

of Puu Hawaiiloa and adjacent lava ridges, the dune ridges along the shore, and the coral flats.

That part of Ulupau which is above 200 feet consists of typical steep slopes of tuff. The east facing inner slopes of the larger crater remnant are only slightly broken by gullies and slope at angles of 30 or 35 degrees. The outer slopes are somewhat more deeply channelled. The areal form

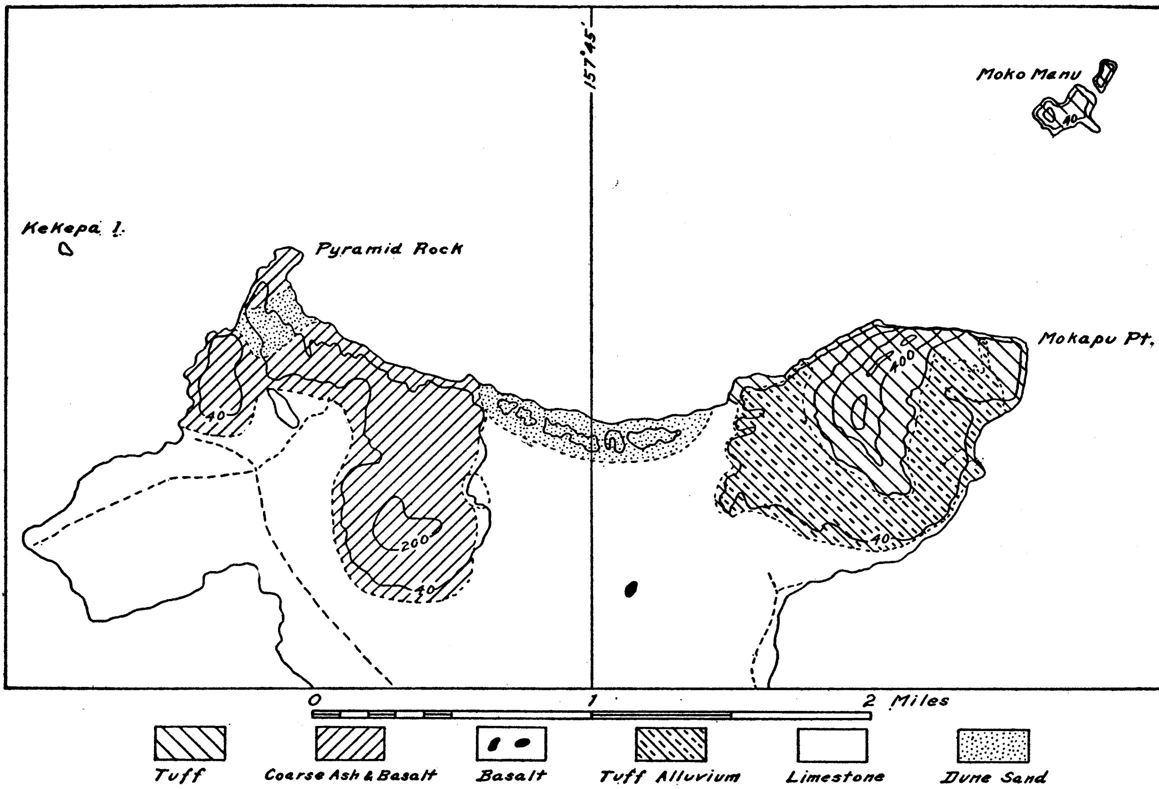


FIGURE 24.—Map showing areal geology of the Ulupau district.

of the upper part of the remnant is typical of the leeward and culminating peaks of crater rims in Oahu. Though its general form is crescentic, the highest point is situated at a slightly rounded angle which extends to the leeward of the principal circle of the crater rim. Below the highest point on the outside, the slopes of the crater cone are somewhat more convex than elsewhere and on the inner side the slopes are nearly plane across this thickened part of the crater. At the north for a distance of about a half mile the crater remnant is cut by the sea to a magnificent cliff 200 to 500 feet high, having everywhere a slope of over 75 degrees and in

places overhanging for 100 to 200 feet (Pl. XVIII, *B, C*). The gap between the larger and smaller remnants is nearly 200 feet high at the point where the gentle inner slope ends abruptly at the crest of the vertical sea wall. The east face of the smaller crater remnant is a similar cliff of less height which declines southward, flanked at the foot by a conspicuous marine bench some five feet above sea level. There is no such bench off the north shore of Ulupau—the cliff extends downward with a slight outward flare to a point at least ten feet below sea level to a bench composed of large, rounded blocks of tuff. As seen from Ulupau Head, the Moku Manu islands rise steeply on all sides from a marine bench now 5 to 10 feet above sea level and 10 to 50 feet in width. The cliffs are 50 to 150 feet high (Pl. XVII, *C*).

On the southeast, south, and southwest sides from the 200-foot contour down to within 25 or 30 feet of sea level Ulupau Head is flanked by relatively smooth graded slopes of alluvial waste from the higher crater mass. In the district between the two remnants and just east of the main summit of the head, these alluvial slopes are deeply cut by a number of large gullies but elsewhere they have not been dissected appreciably. From the west foot of Ulupau Head, short dunes, 40 to 100 feet high, extend westward in a curving line for about a mile. The shoreward parts of these dunes are in part stabilized by vegetation, little of the sand being found over a thousand feet inland.

The main crater of Puu Hawaiiloa is a fairly symmetrical cone, somewhat broken down and gullied on the northeast face. The ridges which extend north and west from the crater are generally strewn with rough lava blocks and covered with scraggly shrubs. Surrounding the higher land areas is a low plain 5 to 20 feet above sea level which is mainly underlain by reef rock and strewn with drifted sand and thin alluvial soil from the tuff and lava. The lower parts of this plain are composed of alluvial material filling reentrants of the old reef; the higher parts are of sand and the thicker alluvial soil. Those of medium elevation are the surface of the reef and are dotted with the jagged, cuspate points of the weathered reef rock. Round the margins of the plain are low cliffs alternating with sand beaches.

AREAL AND STRUCTURAL GEOLOGY

Four rock formations are of importance in the Ulupau district: the Ulupau tuff, the Puu Hawaiiloa agglomerate and lava series, the Ulupau alluvium, and the reef rock and its modern derivatives. The reef rock fragments in the tuff indicate a reef rock mass here antedating the tuff.

The tuff of Ulupau Head is comparatively coarse palagonitic rock which is conspicuous for the amount of secondary calcium carbonate. No very large bombs were seen in the tuff, its coarseness being in its average grain rather than in the maximum sizes. The predominating color is lavender gray, resulting from the blending of the purple of the palagonite and basalt fragments with the bluish white calcite. Much of it as seen in the hand specimen is a brilliantly mottled rock. The principal and westernmost remnant of the crater consists wholly of outward dipping beds, such in-dipping strata as were once present having been removed by erosion or covered by alluvium in the lower slopes. Dips of from 25 to 35 degrees are common throughout the upper part of the rim. The smaller remnant of the crater which forms the northeast point of Ulupau Head is composed of beds which dip mostly toward the center of the crater. Along a considerable part of the east facing cliff, erosion has reached a line just short of the structural crest and there remains a zone of some 50 feet in width of beds which dip outward at low angles. Erosion in the north-facing cliff has long since cut away all outdipping beds and the structural crest, and has removed so much of the in-dipping beds that the highest part of the north rim stands less than 150 feet above the sea.

The upper part of the crater of Puu Hawaiiloa and all of the related ridges to the northwest are composed of lava flows of a dense, dark gray basalt. The steepness of the crater suggests that much of the interior is composed of pyroclastic materials. Coarse agglomerate consisting of lapilli and bombs ranging up to 10 cm. was found at one exposure under the lava at about 125 feet above sea level on the northeast side of the crater. It seems probable that the bulk of the material composing the crater is pyroclastic and that here as elsewhere small masses of flow lava followed the coarser explosive materials. On the northeast flank of Puu Hawaiiloa about 10 feet of tuff are exposed. This tuff may have been erupted from Puu Hawaiiloa during its explosive stages. The lack of any known Ulupau tuff on the plain to the northeast favors this interpretation. But since this locality is in direct line with the drift of trade winds from Ulupau, intervening areas may not have been built above sea level with tuff. If this be Ulupau tuff here mantled on an elevated area, it would indicate that Puu Hawaiiloa is in part at least as old as Ulupau and it seems probable that the first eruption of Puu Hawaiiloa and that of Ulupau were essentially contemporaneous. On the other hand, the attitude of the Puu Hawaiiloa secondary flows on the slope to the north and west indicates that they could not have been formed when the sea was 40 feet higher than now. Moreover the fact that these rocks are nepheline bearing suggests that they may be contemporaneous with the Punchbowl—Roundtop—Rocky

Hill series (p. 75), and consequently that the Puu Hawaiiloa flows are much more recent than the principal Ulupau tuff.

In no other crater of Oahu is the alluvial and colluvial material flanking the slopes so well exposed and its relations to the tuff so well indicated as in Ulupau. Here it has proved practicable to map the alluvium. (See fig. 24.) Along the entire sea margin this alluvium is exposed in cliffs 25 to 50 feet high and it is almost equally well displayed in deep gulches which trench the crater bowl. It consists of a poorly assorted tuff gravel deposited in rather uniform but faintly defined beds. The material is wholly tuff and, unless its relations are known, it is not easy to distinguish from an old, weathered tuff. The principal difference is that the cobbles of the gravel which consist of coarse tuff are far more numerous than are accessory masses of an early tuff in any late tuff found in Oahu. The landward margin of the alluvium laps up on the crater rim to an elevation of nearly 200 feet. It once projected slightly north of the present north cliff of Ulupau Head at the place where the rim is now cut away. At the southern point of the east remnant of the crater rim the alluvium overlies the steeply dipping inner beds of tuff. At a point one-half mile south of the north cliff, the alluvium overlies a marine mud on the surface of which corals were growing at the time the alluvium was deposited. The contact is about 35 feet above sea level and indicates that Ulupau Head had been formed and parts of the east rim destroyed while the sea still stood at the 40-foot level. It appears from the relations of the alluvium that the cutting away of the east rim greatly augmented erosion and formation of the alluvium inside the crater.

Coral reef rock fragments in the Ulupau tuff show that the eruption took place through a vent in an ancient reef. Alluvium now lies on marine mud surfaces, supporting a feeble coral growth. But since Ulupau Head is now areally smaller than it was during the 40-foot stand of the sea, the reef which was growing at that time and just after the eruption has been destroyed. More recent reef rock, forming a plain up to about 15 feet above sea level, is widespread southwest of Ulupau Head. Associated with it is considerable marine calcareous sandstone and conglomerate containing fragments of tuff and basalt bomb pebbles. It grades upward in places into eolian limestone of contemporaneous origin.

Likewise reef rock lies off the present coast and its similar beach and dune derivatives lie along the shore. The calcareous series of rocks and the alluvial series are everywhere intermingled, each probably representing in one part or another the entire time since the Ulupau eruption.

SUMMARY OF GEOLOGIC HISTORY

Eruption of Ulupau Head and Puu Hawaiiloa took place before or during the 40-foot stand of the sea. The destruction of a tuff cone in a situation such as that of Ulupau Head is so rapid, relative to other geologic processes, that it seems unlikely that it has survived from any previous relation of land to sea. The two eruptions may confidently be referred to the time of the 40-foot stand. Wave erosion cut through the east rim, which was low, perhaps almost absent as at Koko Crater, and coral reefs commenced growth on the eroded bench. At some time after the east rim had been cut away, great quantities of alluvium were deposited on the flanks of the remaining parts of the rim. The next event was the uplift of the island to a position about 15 feet lower than now. During this stage erosion of the exposed parts of Ulupau Head continued at the lower level and cut away all parts of the higher bench, except those now covered by the gravel. Stream erosion during this epoch and continuing to the present time has dissected the gravel fans flanking the crater. Coral reefs extended at this time over the present area of the Mokapu Peninsula. A less vigorous transportation of tuff detritus continued to this epoch and the finer material was strewn over reef plain. Probably the flow lavas from Puu Hawaiiloa are contemporaneous with the later Punchbowl flows.

Finally a depression of sea level brought the land to its present position permitting the growth of reef-forming organisms and the formation of beaches and of sand dunes.

PETROLOGY

By

CHESTER K. WENTWORTH AND A. A. PEGAU

BASALT

Megascopically, the basalt of the several secondary flows of Oahu shows relatively little variation, being a moderately vesicular, dense black or dark gray rock with small olivine crystals. It differs little, if any, from the olivine basalt of which the Hawaiian islands are chiefly formed. No density determinations of the basalts were made but it is probable that these rocks accord closely with the lava rocks of Hawaii, which were found by Washington [25] to have an average specific gravity of 2.940 and to range from 2.843 for all the lavas, both basalts and trachytes, of Kohala, to 3.021 for the basalts of Hualalai.

DIAMOND HEAD CRATERS AND DIKES

No. 455. Olivine diabase from west side of Kaimuki crater. No. 455 has a typical diabasic or ophitic texture, and is made up of laths of plagioclase feldspar of which the largest crystals measure 0.9 Augite of a brownish tint in irregular grains, fills the interstitial spaces and olivine is present as euhedral to subhedral crystals and grains, the largest crystals measuring 1.5 mm. by 0.5 mm. Magnetite is also present. The feldspar exhibits both carlsbad and albite twinning and was identified as labradorite. The olivine exhibits variable amounts of alteration to a brownish material, limonite in part and probably bowlingite in part. Augite has its usual appearance. Magnetite occurs in grains averaging 0.1 mm. in diameter, rather larger than usual in these lavas. Measured by the Rosiwal method, using a recording micronometer, gave the proportions: augite, 34.27 o/o; feldspar, 41.64 o/o; olivine, 19.28 o/o; magnetite, 4.81 o/o.

No. 478. Olivine diabase from southwest of Kaimuki. Crater at Campbell and Kapahulu streets. No. 478 is very similar to No. 455, except that the augite is relatively more abundant than olivine and the olivine exhibits less alteration.

No. 98. Fine grained porphyritic diabase from dike on west side of Kupikipikio Point. No. 98 is distinctly finer grained than Nos. 455 and 478. The matrix is made up chiefly of lath-shaped plagioclase feldspars and augite square sections. The phenocrysts are chiefly olivine, the largest 1 mm. by 0.6 mm. Many of the larger ones have a very irregular form having cavities filled with the ground mass material which suggest partial absorption of the original crystal. Alteration to limonite and probably bowlingite is common.

No. 102. Fine grained porphyritic olivine diabase from Kupikipikio flow. No. 102 is very similar to No. 98, although the alteration of olivine is more marked. The resulting mineral, found to be nearly uniaxial and negative, is believed to be bowlingite.

[25] Washington, H. S., Petrology of the Hawaiian islands, Am. Journ. Sc., 5th ser., vol. 6, p. 361, 1923.

No. 1955. Vesicular porphyritic olivine basalt from summit of Mauumae crater. No. 1955 consists of a very vesicular fine grained ground mass studded with phenocrysts which are mainly olivine and subordinately augite. Olivine, the chief phenocrystal constituent, occurs as euhedral to subhedral crystals and anhedral grains. Some of the crystals show excellent prismatic habit, with pyramidal termination; many of them show vermicular pores, rimmed with a rusty brown alteration product (Pl. XIX, *A*). The largest crystals measure 1 mm. by 0.2 mm. Augite occurs both as phenocrysts and in the ground mass. The largest grains are 0.4 mm. in diameter. In addition to augite the ground mass contains feldspar, magnetite and probably glass. The feldspar could not be identified.

Punchbowl

No. 165. Vesicular, porphyritic limburgite from outcrop near road loop on Punchbowl rim. No. 165 is composed of a very fine grained mass, chiefly augite and magnetite, studded with phenocrysts of olivine and augite. The vesicles are rather numerous and average about 0.5 mm. by 0.3 mm. Olivine comprises about half of the phenocrysts. It occurs as euhedral to subhedral crystals and anhedral grains. They range from 1 mm. to 0.1 mm. in diameter. Some of the crystals show good crystal outlines, others exhibit a jagged outline, suggesting absorption and many crystals show a heavy brown to black alteration rim of limonite, with a slight development of a mineral thought to be bowlingite. Double refraction of the olivine is about 0.035 and it is optically negative, suggesting high iron content. Augite is the chief constituent in the ground mass, where it occurs as rod like grains, and is a subordinate phenocryst mineral, the largest grains averaging 0.5 mm. in diameter. All show distinct zonal structure and irregular extinction. They are of the usual color, subhedral to anhedral in form, and are relatively less altered than olivine. The matrix is made up of augite, magnetite and a colorless, weakly birefringent mineral, occurring occasionally as squares, with parallel extinction and identified as nepheline. There is also developed from the augite a greenish, rather amorphous weathering product.

No. 1042. Vesicular porphyritic limburgite or nepheline olivine basalt from near breach in Punchbowl rim (Pl. XIX *B*). No. 1042 is similar in appearance to No. 165 with possibly fewer vesicles and phenocrysts. It is also similar in composition, the ground mass being made up chiefly of rod-like grains of augite, and a mineral of low index and birefringence which is probably nepheline. Probably some feldspar is present but none was identified as such. In addition to these magnetite and a little olivine occur. The nepheline occurs as irregular to square grains, averaging 0.01 to 0.03 mm. in diameter. The phenocrysts are similar to those in No. 165; the olivine, more porous than in No. 165 but less altered, occurs in crystals measuring 1.5 mm. by 0.8 mm. and optically negative. Augite appears as subhedral to anhedral grains with zonal structure and zonal extinction. The largest crystals measure about 0.5 mm. by 0.5 mm. Magnetite is found in the ground mass and as inclusions in the olivine. Measurement by the Rosiwal method gave the proportions: phenocrysts, 24.2%; ground mass, 75.8%.

Tantalus—Roundtop

No. 1967. Nepheline olivine basalt (limburgite?) from Manoa dike flow near Mills School. No. 1967 is a porphyritic, vesicular fine grained rock of which the phenocrysts are chiefly olivine, with subordinate amounts of augite and irregular patches of fine grained calcite. The fine grained ground mass is made up of nepheline, augite, magnetite, and secondary calcite. Olivine comprises most of the ground mass, some of the crystals reaching 1.5 mm. in length. Many show gas bubbles and

are relatively fresh, showing little alteration. Some have inclusions of magnetite. Augite is rarely of phenocrystal size, although it makes up a large part of the matrix, where it has its usual appearance of rod like crystals and irregular grains. Secondary calcite is present in irregular elongated patches several millimeters long made up of fine grained material. Nepheline comprises nearly half the ground mass and occurs as squares and rounded grains 0.02 to 0.05 mm. across, of which many contain inclusions of magnetite. Magnetite is abundant and of larger size than usual, some of the grains being 0.25 mm. in diameter.

No. 1985. Nephelite basalt from west face of Rocky Hill (Pl. XIX, *C*). No. 1985 is distinctly different in appearance from No. 1967, being much more vesicular with the vesicules occupying one-third to three-fourth of the volume. The ground mass is very dark, and contains phenocrysts of a much altered olivine. The matrix is irregular and ropey in appearance. Olivine comprises most of the phenocrysts and occurs as good crystals, the largest measuring 1.5 mm. by 3 mm. Many have longtitudinal pores and alteration is frequent, beginning either from the outside or from the pores. The alteration material is reddish brown in color, very pleochroic, (reddish brown to light yellow) extinction simultaneous with that of olivine, index and birefringence lower than balsam, and was identified as bowlingite. The matrix is nearly opaque, though augite and nepheline were identified. Magnetite is abundantly present dotting the whole mass. A bladed mineral of low index thought to be a feldspathoid is present. The ground mass is largely glass.

Koko Craters and Dikes

No. 1919. Vesicular gabbro from Koko dike on south flank of Koko Crater. No. 1919 has a vesicular, fine grained ophitic texture. The minerals include feldspar, augite, magnetite, secondary calcite and olivine. Feldspar occurs as laths that rarely exceed 0.2 mm. in length and make up most of the ground mass. The extinction angle was not obtained; all crystals show carlsbad twinning. Augite occurs as grains and needle or rod-like crystals, the largest of which measure 0.3 mm. and 0.2 mm. The color is brownish green. Secondary calcite is sparingly developed in patches and around some of the vesicles. Olivine is only sparingly developed as anhedral grains about 0.1 mm. by 0.1 mm. The vesicles are usually rimmed to a depth of 0.02 mm. to 0.05 mm. by a clear isotropic substance having an index lower than balsam and which is probably glass. Some of the vesicles are filled with a spherulitic glass, others are partially filled with secondary calcite. These vesicles occupy about one-third of the volume of the rock.

No. 733. Vesicular olivine gabbro from block on tuff surface southeast of Koko Head summit. No. 733 differs from No. 1919 in being less vesicular, in the large size of the phenocrysts, and the greater abundance of olivine. The texture is porphyritic, fine grained ophitic. The matrix is composed essentially of laths of feldspar 0.1 mm. by .01 mm., rod-like anhedral grains of augite, usually light brown to brownish green in color, magnetite, probably titaniferous, and small amounts of olivine. The phenocrystal material is made up chiefly of olivine and to a less extent of augite. Olivine occurs as subhedral to anhedral grains 1 mm. by 0.6 mm. to .01 mm. by 0.1 mm. and contains many inclusions of magnetite. The mineral is fairly fresh and shows little alteration. Optic sign negative, birefringence (0.035-0.040). Augite, of a brownish to greenish brown tint, is present in subhedral to anhedral grains that average smaller than those of olivine.

No. 769. Vesicular olivine basalt from block south of Koko Head summit. No. 769 is a finer grained rock than No. 733 and its phenocrysts are fewer in number. The matrix or ground mass is nearly cryptocrystalline, made up of very small laths of feldspar, small rods of augite, grains of magnetite, and a cloudy

interstitial material. The phenocrysts rather sparingly developed are mainly augite with olivine subordinate. Olivine, the largest grains measuring 0.5 mm. by 0.4 mm., occurs irregularly distributed through the ground mass and partially filling the vesicles. Augite grains average 0.3 mm. by 0.2 mm. in diameter. The vesicules average 0.2 mm. in diameter, the largest being about 1 mm. They contain no rims and occupy about one-fourth of the mass.

Ulupau Craters

No. 2022. Nepheline olivine basalt (limburgite?) from Puu Hawaiiloa flow west of Ulupau. No. 2022 is coarser grained than most basalts of Oahu. The texture is determined by the square grains of nepheline, the femic minerals (augite and olivine) filling the interstitial spaces together with abundant irregular patches of magnetite. The minerals are chiefly augite and nepheline with subordinate olivine; magnetite, and secondary calcite being accessory. Augite, which forms most of the slide, occurs as irregular grains filling the interstices between the nepheline grains. It is of an olive brown to lavender brown color, with pleochroism commonly developed. These phenomena together with its slightly higher double refraction, suggest a titanium variety. Nepheline, the next most abundant mineral, occurs as square sections to irregular grains that average 0.1 mm. by 0.1 mm. and show parallel extinction and low double refraction. It is regularly distributed through the slide. Olivine is irregularly distributed through the slide, the largest grains measuring 1 mm. by 0.7 mm., one-third to one-half the amount of augite. Alteration though present is less pronounced than usual. Magnetite is rather more abundant than usual, occuring as irregular patches and grains. Secondary calcite is sparingly present as irregular patches that show distinct rhombohedral cleavage with high magnification. Some of the ground mass is filled with glass in isolated patches. It is light reddish brown in ordinary light and exhibits a spherulitic texture under crossed nicols. No feldspar was noted.

No. 2030. Olivine nepheline rock—Limburgite? from agglomerate of Puu Hawaiiloa slope. No. 2030 is a finer grained porphyritic rock made up of olivine, nepheline, augite, secondary calcite and magnetite. The ground mass consists of small rod-like crystals of augite, euhedral to anhedral grains of magnetite and irregular grains of nepheline. The nepheline is slightly altered to an indefinite cloudy material. The phenocrystal material is olivine and nepheline. Nepheline occurs as squares and laths and average 0.3 mm. in diameter and contains numerous inclusions of euhedral magnetite. Olivine, the most abundant phenocryst mineral, occurs as euhedral crystals and anhedral grains. The largest crystals measure more than 1 mm. in length. It shows very little alteration and contains frequent inclusions of magnetite. Some of the crystals have irregular cavities. Secondary calcite is rather abundantly developed as irregular grains that rarely exceed 0.5 mm. in diameter. Much of the slide is clouded by some secondary fine grained product, probably kaolinite.

Summary of Characteristics

The basalts studied show a considerable textural variation as is to be expected from the variety of conditions under which they were formed from a number of different magmas. Having been collected from places near to the vents, they show how universally in these rocks certain minerals such as magnetite and olivine have crystallized out before the molten lava reached the surface.

The most notable peculiarity of composition is the presence of nepheline in specimens from Punchbowl, from Rocky Hill, Manoa dike, and Puu Hawaiiloa. From other considerations it has seemed that the late Punchbowl eruption and the Tantalus-Roundtop-Rocky Hill eruptions were contemporaneous. The composition of the lavas supports this view and the fact that the only other nepheline bearing lavas among the rocks studied are those of Puu Hawaiiloa suggests strongly that this crater, which is almost directly in line with the Rocky Hill-Tantalus craters, was also active at the same time.

Nepheline basalts are reported by Cross [26] from Punchbowl, Rocky Hill, one of the Salt Lake craters, Diamond Head, and a dike near Nuuanu Pali. No dike in place was found in the Diamond Head region and the "Diamond Head dike" mentioned by Cross is an assemblage of loose blocks which may be the result of human transport. It is significant to note that in five specimens of basalt from the Diamond Head region (Nos. 455, 478, 98, 102, and 1955) no nepheline was found.

The presence of nepheline rocks near Nuuanu Pali, on a line between Rocky Hill and Hawaiiloa is strongly suggestive that these dikes and pyroclastics are part of the Tantalus-Rocky Hill series and formed contemporaneously with them.

BLACK ASH

Megascopic Features

In its unaltered condition the black ash of Oahu consists of nearly jet black droplets, and broken stringlets of vesicular basaltic glass. The vesicles are commonly elongate in the direction of extension of the plastic material as the droplets were formed. Much of the existing black ash is stained red brown by iron compounds, or white by the deposition of secondary calcium carbonate and cemented to greater or less degree by these minerals. Much of the very fresh black ash has iridescent colors on the smooth surfaces of the droplets, and in these specimens the edges and corners of the fragments are seen to be altered to reddish yellow palagonite. The droplets and other forms assumed in cooling are usually much broken, the commonest form being a rude section of an elongate, somewhat fluted, vesicular rope such that the fragment is bounded by a smooth and commonly unbroken prismoid surface and by two basal surfaces in which many vesicles are exposed in section. Commonly the lengths of the prismatic sections are nearly equal to the diameters, the general sizes of fragments

[26] Cross, Whitman, Lavas of Hawaii and their relations, U. S. Geol. Sur., Prof. paper 88, pp. 21-23, 1915.

being determined by the conditions of expulsion and cooling. The smaller droplets have more largely escaped breakage and appear as balls, dumb-bells, and spiked globules, though these ideal shapes are everywhere subordinate to the less regular and somewhat broken ones.

The black ash ranges in coarseness from a maximum of about 1 cm. down to certain deposits in which no fragments are over a millimeter in diameter. The variation in a single exposure or even in a single locality is commonly much less than this. The bedding of the black ash is of an indefinite sort, it lacks prominent beds or planes of separation but is exceedingly regular.

Physical Properties

The mechanical composition of black ash is shown in figures 25-28, inclusive. A number of the samples show an approach to an ideal composition

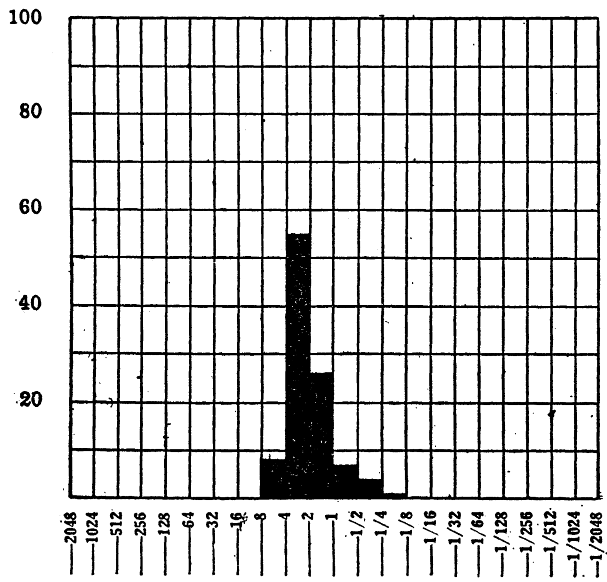


Figure 25.—Mechanical composition diagram showing ideal composition which many of the black ash samples approach.

in which upwards of 50 per cent is in one grade. There is a single grade coarser than this maximum and that contains ideally less than 10 per cent. The grades smaller than the maximum are about three in number and amount roughly to a half, an eighth, and a twelfth respectively of the maximum grade. (See figs. 25 and 26, *a*.) This composition appears to be due to a process of winnowing, whereby at any point there fall all the

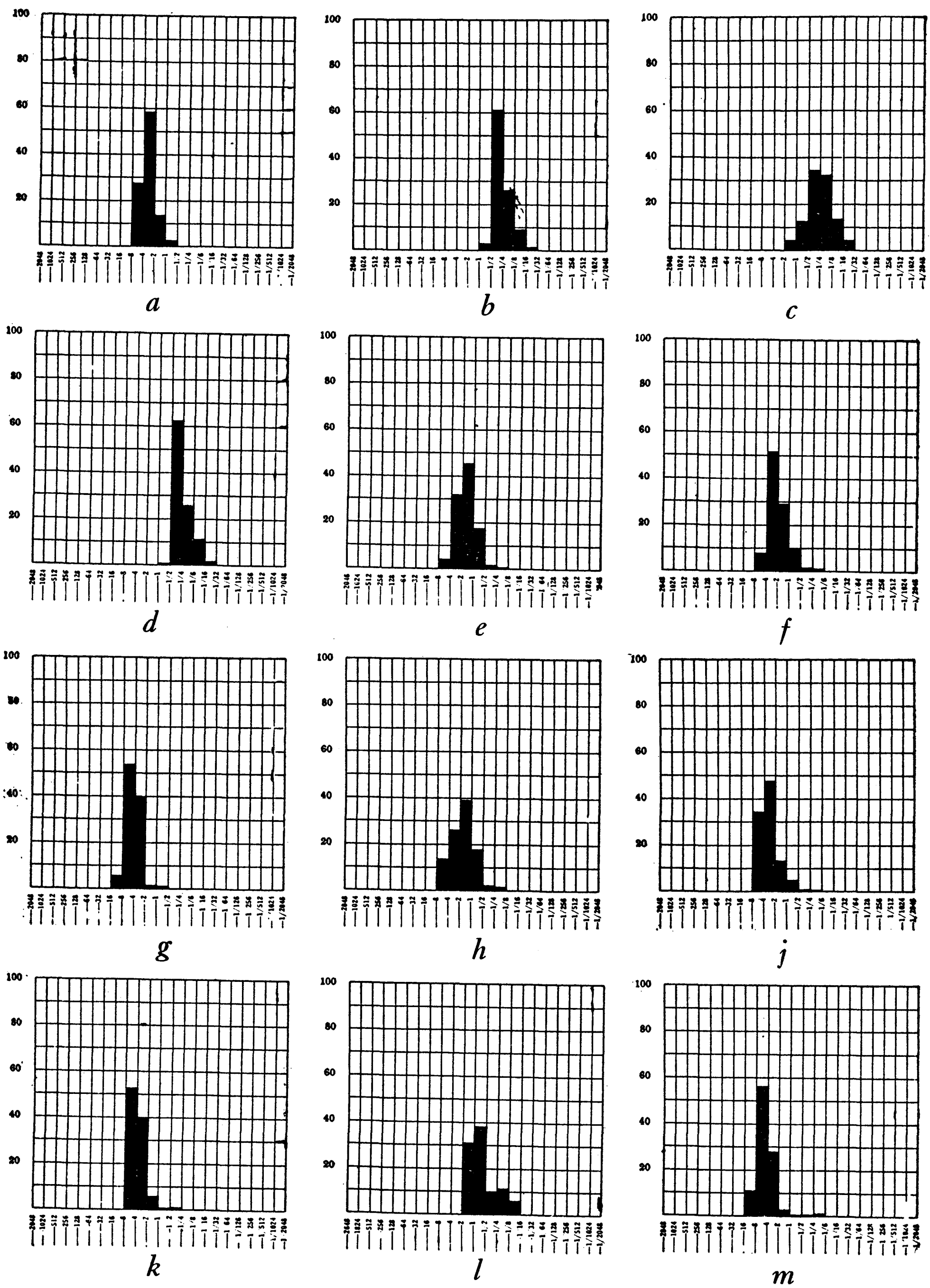


FIGURE 26.—Diagrams showing mechanical composition of black ash, *a*, No. 14, from Tantalus; *b*, No. 50; c, No. 84, and *d*, No. 85, from Diamond Head; *e*, No. 161, from Punchbowl; *f*, No. 515B, from east of Punchbowl; *g*, No. 535, from Tantalus; *h*, No. 549, *j*, No. 559, and *k*, No. 588, from Roundtop; *l*, No. 841, from Koko Crater slope; *m*, No. 1854, from Koko Crater. Figures at the right indicate percentages; figures at the bottom indicate grade sizes in millimeters; numbers refer to samples described in the text.

coarser fragments attaining that distance from the vent and progressively lesser parts of the finer grade. The sharp upper limit of the sizes of fragments is due to the completeness with which all coarser material has settled out closer to the vent and the long tailing out of finer grades is due to the settling out of small parts of the finer debris from the lower air currents, and is analogous to incomplete washing in a settling type of elutriator whereby the coarse grade sought is contaminated by progressively lesser amounts of the finer and slower settling grades. Similar sorting action takes place in streams and ocean currents but perhaps rarely under so simple and favorable conditions as in the case of these ash deposits.

The specific gravity of the black ash as a rock and in fragments and the resulting porosity are shown in Table 11.

TABLE 11.—SPECIFIC GRAVITY AND POROSITY OF BLACK ASH

NUMBER OF SAMPLE	DIAMOND HEAD			PUNCHBOWL					AVG.
	50	85	161	515 B 1	515 B 2	515 B 3	535	559	
Gross specific gravity as poured into graduate	1.30	1.08	1.08	.99	1.00	1.00	.82	.83	1.02
Net specific gravity of fragments as broken	2.44	2.37	2.57	2.39	2.40	2.47	2.25	2.41	2.41
Porosity including open vesicles of fragments	.470	.544	.581	.586	.585	.597	.637	.655	.577

As is to be expected, the black ash exhibits great variations in gross specific gravity and porosity. The net specific gravity of the fragments is much less variable, though still showing considerable range due to differing vesicularity and breakage. Very little if any of this material could be cemented and retain a sufficiently low specific gravity to float. The composition of the basaltic glass is such as to make a determination of its specific gravity exceedingly difficult. Included crystals of magnetite and olivine raise the gravity and vesicles lower it. Both crystals and vesicles extend to very minute dimensions. Such determinations as were made gave specific gravities of from 2.7 to 2.9 but these can hardly have great value with reference to the pure glass.

Microscopic Features

Samples of black ash studied under the microscope include fourteen detrital specimens and three thin sections of cemented ash. Descriptions of these follow:

No. 50. Fine black ash from southeast lower slope of Diamond Head. No. 50 is a fine grained ash of nearly typical mechanical composition (fig. 26, *b*). The coarser grades consist of twisted glass fragments with olivine crystals, and secondary calcite. In the finer grades considerable magnetite in crystals and grains is found.

No. 84. Black ash from southeast slope of Diamond Head. As compared with No. 50 the material of No. 84 is less well sorted (fig. 26, *c, d*) and appears to have been slightly transported by streams or slope wash. The coarser grades are mainly of black ash fragments with secondary calcite and tuff fragments. Magnetite is present in the finer grades.

No. 161. Black ash from a point a few yards east of Punchbowl road loop. No. 161 is a moderately well sorted coarse cinder-like ash (fig. 26, *e*). The coarser grades consist of moderately fresh black and iridescent glass fragments. In the finer grades a few olivine crystals appear and the glass fragments become strongly magnetic from included magnetite.

No. 515 B. Coarse black ash from point one-half mile east of Punchbowl. Probably from Roundtop vent (Pl. XXI, *A*). No. 515 B is a well sorted ash, having over 50% in the 2-4 mm. grade (fig. 26, *f*). The coarser grades consist of shiny black sections of stringlets and vesicular bulbs of glass. In the finer grades more unbroken droplets, dumb-bell and such shapes are seen as well as olivine crystals and some fragments so charged with magnetite as to be attracted by the horseshoe magnet.

No. 535. Weathered black ash from road cut near Tantalus summit. The material of No. 535 is rather well sorted, mainly in the 2-8 mm. range, and consists of pinkish buff fragments of palagonite containing small nuclei of glass (fig. 26, *g*). The structure is vesicular and the forms of fragments are well preserved though the bulk of the mass has gone over to palagonite without any considerable cementation of the beds.

No. 549. Fine black ash from southeast side of Roundtop road a half mile northeast from end of Makiki Street. No. 549 is relatively poorly sorted, four grades containing over 12% and the larger part being in grades larger rather than smaller than the maximum (fig. 26, *h*). All of its particles, both in large and small sizes, consist of rounded pellets or aggregates of very fine ash mostly less than 0.62 mm. in size. These were probably formed by falling rain at the time of the eruption and this circumstance probably explains the poor sorting and departure from the compositions shown by most of the ash samples.

No. 559. Coarse black ash from southwest end of Roundtop. No. 559 consists of glass droplets and fragments which have stony gray surfaces but are bright glass in the interior. The larger fragments are very vesicular; the smaller less so and these are magnetic with contained magnetite (fig. 26, *j*).

No. 588. Coarse ash from east flank of Roundtop (Pl. XXI, *B*). No. 588 is a well sorted dark brown material with corners and edges of a tawny color (fig. 26, *k*). Much of the coarser material and probably most of the finer grades is altered to palagonite. Considerable olivine and small amounts of magnetite are present in the finer grades.

No. 841. Black ash from west slope of Koko Crater. No. 841 is a poorly sorted black sand composed of rounded compact pellets of vesicular black ash (fig. 26, *l*). The larger fragments are rather minutely vesicular and of battered, stony appearance. Medium grades carry an unusual proportion of olivine in battered grains. The finer grades consist of glass and olivine with almost no magnetite.

No. 1854. Coarse ash from gap northwest of Koko Crater. No. 1854 is a well sorted mixture of black, brown, tawny and iridescent, much palagonitized glass fragments (fig. 26, *m*). The larger particles are vesicular throughout. No olivine was noted and the finer debris, like that of No. 841, carries little or no magnetite.

No. 203. Porous gray cemented black ash from southwest flank of Punchbowl. No. 203 consists of fragments of an olivine basalt cemented together with calcite. Most of the mineral grains are surrounded by very fine grained magnetite. The minerals in the calcite matrix include olivine and nepheline chiefly, magnetite. and glass material. No augite or feldspar was identified. Nepheline is rather abundant as euhedral to anhedral crystals. It is present commonly as squares (0.01 mm. by 0.1 mm.) and rarely as hexagons, also as lath shaped rectangular grains that measure 0.3 mm. by 0.1 mm. Some of the rectangular grains may be mellilite, but the index could not be obtained because of the magnetite surrounding them. Olivine is present as subhedral to anhedral crystals, the largest not more than 0.5 mm. in diameter. They are quite fresh and show occasional inclusion of magnetite. Magnetite is present chiefly as fine grained patches, surrounding the other materials. Secondary fine grained calcite, occurs as irregular to spherulitic patches cementing the other material. Some show irregular extinction. Glass occurs as detached, shapeless masses, brownish-red in color, containing small amounts of the other materials. Limonite is also present in small amounts.

No. 1823. Cemented black ash from west slope of Koko Crater. No. 1823 is made up chiefly of irregular pointed and curved fragments of glass, with minor amounts of olivine, magnetite and secondary calcite. Glass occupies about 90% of the mass, light green brown in color, usually porous. The fragments average about 0.2 mm. in diameter. Olivine is sparingly present as subhedral to anhedral crystals, the largest ones 0.5 mm. in diameter; some of the crystals are surrounded by a rim of magnetite, partially altered to limonite. Secondary calcite is very sparingly present as very fine grained masses between the glass fragments. Magnetite is present as irregular grains included in the glass and as rims around some of the olivine.

No. 1870. Cemented glassy tuff from rim of Kalama crater. No. 1870 is a vesicular rock, whose ground mass is made up of a partially palagonitized glass clouded by hydrous iron alterations. This glass contains inclusions of magnetite and olivine. Magnetite occupies a large part of the mass, occurring as euhedral to anhedral grains, many containing circular cavities. Some of the largest grains measure 1 mm. in diameter, though most of them are less than 0.5 mm. in diameter. It includes and is included in olivine. Olivine is not quite as abundant as magnetite and occurs as euhedral to subhedral crystals; some showing an irregular outline due to their partial absorption by the glass. The largest crystals measure 0.1 mm. in length. It shows occasional yellow brown alterations. Calcite is very sparingly developed. One crystal of plagioclase feldspar, showing carlsbad twinning was noted.

Summary

The specimens of black ash described consist of basaltic glass, olivine, magnetite, palagonite, and secondary calcite, in the order named. In some specimens, nearly circular sections of glass predominate; in others, broken shards and angular pieces are most abundant. The olivine crystals are invariably euhedral and range to about 1 mm. in diameter. They include small droplets of glass, euhedral and irregular grains of magnetite, and form a fairly conspicuous part of every sample examined. Magnetite, though commonly in smaller grains than the olivine, is even more generally distributed throughout the black ash rocks. It was the first mineral to crystalize, and continued crystallizing until most of the olivine had crystallized

out. In many specimens it occurs in rounded masses peripheral to the olivine. In a specimen from Punchbowl much nephelite is present, which confirms the view based on field relations that this ash is contemporaneous with the Punchbowl lava flow and the Tantalus-Roundtop eruptive materials.

TUFF

Color, Bedding, and Composition

The tuffs of southeast Oahu range in color from brown or gray to yellow. In the Ridgway [27] color scheme most of them would be classed as "15, yellow orange" and "17, orange yellow."

Within each crater district the colors of the tuff vary considerably; but the different craters show different color ranges, sufficient to determine the source of any large series of specimens. The Diamond Head, Punchbowl, and Koko tuffs are in general very similar in color although some dark brown tuff at Punchbowl is not duplicated, so far as known, at Diamond Head.

The Koko tuff, especially that of Koko Crater, grades from gray, very slightly altered cemented black ash to the most brilliant, reddish resin colored tuff to be found on Oahu. The Salt Lake tuffs in general show grayish, lavender, and dull purple colors and are notably mottled, some specimens showing nearly as brilliant a combination of colors as the well-known Triassic limestone conglomerate ("Potomac marble") of Maryland and Virginia. The Ulupau tuff, on the whole, is somewhat less brown or yellow and more gray than the Diamond Head or Koko tuff.

The bedding of the tuff may be described as a gradual transition, layer by layer, between beds of differing texture or composition. (See also p. 26.) That it possesses a very uniform and continuous bedding is well shown in many places by differential weathering or by eolian abrasion. But the finer laminae thus brought into relief do not as a rule differ sharply enough to be apparent in most outcrops and the tuff commonly appears as a comparatively weak, homogeneous, and massive-bedded rock.

The Oahuan tuffs consist essentially of palagonite produced by the alteration of the basaltic glass of relatively fine grained black ash. They contain in addition varying amounts of unaltered basaltic glass (megascopically apparent in a few specimens only), a very few bombs of basalt, numerous accessory fragments of basalt, accidental masses of reef rock and detrital limestone, bombs of olivine, augite and other heavy minerals, olivine phenocrysts, magnetite crystals and grains, and fragments of older tuffs.

[27] Ridgway, R., Color standards and color nomenclature, Washington, 1912.

A few beds are made up of palagonitized ash pellets produced by the accretion of finer ash particles while falling or by the accumulation of materials as it rolls down steep slopes immediately after falling. Such pellets, some of them as much as an inch in diameter, have a nuclear fragment which is commonly much less altered than the finer material which surrounds it. In addition to the original constituents and the palagonite derived from the glass nearly all the tuff carries considerable quantities of secondary calcium carbonate which has played a fundamental part in lithification.

Density and Porosity

Densities (strictly speaking, specific gravities) were determined for 37 specimens of tuff as shown in tables 12 and 13. The specimens were first weighed in air, then coated with paraffin and weighed both in air and in distilled water at approximately 20° C. Bubbles formed in the paraffin coating were removed with a hot wire. A few duplicate determinations showed agreement within about 1 per cent, a satisfactory accuracy considering the great variability of the rock. Densities varied from 1.59 grams per c.c. or 99 pounds to the cubic foot, for a very porous recent tuff from Koko Crater to 2.18 grams per c.c. or 136 pounds to the cubic foot, for a compact and much older tuff deeply buried in the north slope of Tantalus. The variations in density are due largely to variations in porosity, as shown by the relatively slight variation in grain density. Grain density was determined in a picnometer using the finely powdered rock, and varying from 2.47 to 2.67, or a total of less than 8 per cent of the average. Porosity varied from 13 to 37 per cent or 80 per cent of the average and density as stated above from 1.59 to 2.18 or slightly over 31 per cent of the average.

The average densities of the tuffs of the several crater groups show a progressive increase from the lighter Koko tuffs through the Diamond Head, Salt Lake, Punchbowl, and Ulupau tuffs to the relatively heavy material from the north flank of Tantalus. These densities probably represent a number of factors other than age, but it is apparent from inspection of corresponding thin sections and from field relations that higher densities are mainly due to the more extensive mineralization which has taken place in the older and more deeply buried tuffs.

TABLE 12.—DENSITIES OF OAHUAN TUFFS

CRATER GROUP	SPECIMEN NO.	DENSITY
Diamond Head	15 A	1.91
	15 A	1.92
	23	1.93
	267	1.99
	446 A	1.93
	446 B	1.89
	446 C	1.87
	27	1.96
	Average	1.925
Punchbowl	139 A	2.04
	139 B	2.13
	151	1.99
	Average	2.053
Salt Lake	619 A	1.85
	619 A	1.88
	619 B	1.80
	624 A	2.06
	624 B	2.14
	624 C	2.18
	1128	2.03
	1150	1.94
	1176	2.05
	Average	1.992
Tantalus—Roundtop	1994	2.06
	1994	2.18
	Average	2.12
Koko Crater	122	1.74
	126	1.86
	720 A	2.01
	720 B	1.88
	880	1.87
	1852	1.78
	1920	1.86
	1929	1.73
	1949 A	1.84
	1949 B	1.93
	1949 C	1.86
	1949 C	1.84
	1997	1.59
	2620	2.16
	Average	1.853
Ulupau	2018	2.06
	Grand Average	1.939

TABLE 13.—DENSITIES, GRAIN DENSITIES AND POROSITIES OF 5 SPECIMENS OF TUFF

SPECIMEN AND LOCALITY	DENSITY	GRAIN DENSITY	PER CENT POROSITY
624 C (Salt Lake)	2.18	2.67	18.3
139 B (Punchbowl)	2.13	2.47	13.8
15 A (Diamond Head)	1.92	2.58	25.6
1997 (Koko district)	1.59	2.54	37.4
2620 (Manana Island)	2.16	2.50	13.6
Average	2.00	2.552	21.7

Microscopic Features

The microscopic character of the tuffs is indicated by the following descriptions of 18 thin sections.

No. 23. Palagonite tuff from south slope of Diamond Head near the coast. No. 23 consists of pellets of palagonitized glass, containing inclusions of olivine, nepheline, and magnetite and cemented together with calcite. Glass occupies over three-fourths of the slide and is present as vesicular pellets, ranging in size from less than a millimeter to several millimeters in diameter. It is highly palagonitized, and is orange to yellow in color (Ridgway 15 to 21 b). The glass is filled with spherulitic to isotropic spherical inclusions. The rims of the pellets are usually dark from fine grained inclusions of magnetite. Nepheline is present as squares and irregular grains usually along the border between the glass and calcite and occasionally as inclusions in the glass. The grains average 0.05 mm. in diameter. Olivine occurs sparingly as irregular grains, the largest 1 mm. long, and contains many inclusions of glass. Some grains are surrounded by, and apparently partially absorbed by glass now in the form of palagonite. Calcite occurs as irregular patches cementing the pellets of glass, making up about one-fifth of the slide, and is also present as spherulitic inclusions in the glass. There are patches of a fibrous low index mineral of uniaxial figure, low double refraction and irregular extinction, probably some form of secondary silica.

No. 15. Palagonite tuff from west slope of Diamond Head. No. 15 is made up of grains and pellets of palagonite, that average smaller than those in No. 23. These are yellow orange (Ridgway 19) in color. Many of the grains show spine-like projections into the interstitial calcite. The glass is more thoroughly palagonitized than in No. 23. Calcite is more abundant, olivine is somewhat fresher, magnetite is more abundant but nepheline is of doubtful occurrence. It also contains spherulitic masses included in the secondary calcite. Measurement by the Rosiwal method gave the proportions: palagonite, 18.52 per cent; glass, 46.55 per cent; olivine, 10.64 per cent; magnetite, 0.43 per cent; calcite, 23.86 per cent.

No. 446. Palagonite tuff from quarry in north flank of Diamond Head near Fort Ruger. No. 446 is composed of pellets and grains of palagonitized glass, many of which are blackened with magnetite inclusions. The unaltered glass is sulphur yellow in color (Ridgway 25). Calcite is sparingly developed, the interstitial spaces are largely filled with the fibrous spherulitic, low index, low double refracting material, some of which shows a faint uniaxial bar. Olivine occurs as subhedral to anhedral grains that average about 0.3 mm. in diameter and are included in and contain inclusions of palagonite.

No. 619A. Palagonite tuff from road cut in lower Moanalua gorge west of Moanalua Gardens. No. 619A is composed of magnetite filled glass pellets, some of which contain inclusions of olivine, others are filled with rod-like grains of augite. The interstitial material is principally an unidentified spherulitic, low index, low doubly refracting material. These pellets contain also circular cavities at times partially filled with calcite, and again with the spherulitic material. Inclusions of mellilite also occur, partially replaced by calcite. Augite when present occurs as rod-like grains that average 0.1 mm. by .05 mm. Olivine is quite abundant in some pellets, as irregular grains, the largest 0.5 mm. in diameter. It is found both in the pellets and in the interstitial spaces, and is often surrounded by and contains inclusions of magnetite. Magnetite is very abundant obscuring in many specimens the color of the palagonite.

No. 624C. Palagonite tuff from Moanalua gorge (Pl. XXII, *B*). No. 624C is composed of palagonite pellets, containing abundant magnetite, olivine, augite and cemented with calcite. The wide interstitial spaces are filled with a beautifully developed secondary mineral thought to be some form of silica. It is spherulitic, has a low index and is doubly refracting. The augite is more abundantly developed in some pellets than in others. Many pellets contain cavities partially filled with secondary calcite.

No. 1116. Palagonite tuff from point one mile southwest of Makalapa and east of railroad. No. 1116 is made up of vesicular pellets of palagonitized glass cemented together with successive calcite growths. The palagonite contains inclusions of nepheline in laths and squares, olivine as irregular grains and vesicles partially filled with calcite which exhibits a concentric growth. Calcite is also developed along cracks in the glass, as narrow ribbons 0.2 mm. wide, many of which extend into the calcite areas in the interstitial portions. The calcite is more coarsely crystalline in the cracks. The glass shows distinct palagonitization changing to orange yellow to reddish brown. Olivine occurs very much as usual, surrounded by and including palagonite. Some grains show excellent crystal outline. Nepheline is abundantly developed in some of the pellets, as squares, laths and irregular grains. Some of the laths may be mellilite though the index could not be determined accurately. Feldspar is very sparingly developed as subhedral grains 0.1 mm. in diameter and is of the labradorite variety. Magnetite is included in the glass, and in all the mineral constituents. (See Pl. XIX, *D* for rocks similar to No. 1116.)

No. 1150. Palagonite tuff from excavation near east shore of Pearl Harbor west of Reservation Gate. No. 1150 is composed of non-vesicular glass dotted with palagonite areas. Olivine and magnetite are present in much the usual way. Feldspar is very sparingly developed as subhedral grains 0.1 mm. in diameter, with a symmetrical extinction of 10 degrees.

No. 139A. Palagonite tuff from road cut on west side of Punchbowl. No. 139A is a vesicular tuff comprised chiefly of pellets of palagonitized glass (Ridgway 16 to 21), that range from less than a millimeter to several millimeters in diameter. These pellets contain numerous globular inclusions, some isotropic, some filled with spherulitic calcite, and olivine. Many of the pellets are partially rimmed by secondary calcite. These rims rarely exceed 0.5 mm. in width. Olivine has the usual appearance, included in the palagonite and partially absorbed by the original magma. It contains magnetite inclusions, and rarely spherulitic calcite is developed in its cavities. Magnetite is rather sparingly developed; occasionally as euhedral, usually as anhedral grains.

No. 139B. Palagonite tuff from road cut in west side of Punchbowl. No. 139B is made up chiefly of a partially palagonitized glass (glass, Ridgway 25), with relatively few vesicles. It contains numerous inclusions of olivine, and spherulitic calcite. Magnetite is relatively rare, occurring frequently as euhedral

grains 0.01 mm. in diameter, rarely 0.5 mm. in diameter, the largest grains containing numerous spherulitic intergrowths of calcite. Olivine occurs as subhedral to anhedral grains, some exhibiting good prismatic terminations. The grains average 0.3 mm. in diameter. Calcite is present chiefly as circular spherules, about 0.01 mm. in diameter, occasionally rimming the glass. These spherules are more numerous in some portions than in others.

No. 151. Palagonite tuff from northeast upper slope of Punchbowl. No. 151 is a rock made up of widely separated pellets partially cemented by secondary calcite. The glass is strongly palagonitized (palagonite orange to yellow, Ridgway 17 to 20), and is filled with numerous globular inclusions, spherulitic to isotropic. Olivine is less abundant than usual, occurring as irregular grains with frequent palagonitized glass and occasional magnetite inclusions. Magnetite occurs sparingly as grains, and as opaque patches 1 mm. in diameter, scattered through the glass. Secondary calcite occurs as irregular patches rarely more than 0.5 mm. in diameter, partially filling the interstitial spaces.

No. 126. Palagonite tuff from west lower slope of Koko Head. No. 126 is made up of pellets containing rather clear palagonite and non-palagonitized glass. The palagonite is orange to yellowish orange (Ridgway 15 to 17), slightly polarizing and irregularly extinguishing. The pellets are very vesicular, the vesicles frequently filled with calcite. The interstices are filled with calcite and isotropic glass, partially altered to a fine grained brightly polarizing material, probably kaolinite. Olivine is present in its usual mode of occurrence, included in and including palagonite. Magnetite while distributed through the whole mass is more concentrated in some portions than in others.

No. 720B. Palagonite tuff from rim crest due west of head of Hanauma Bay (Pl. XIX, *E*). No. 720B is made up of irregular pellets of glass with varying degrees of palagonitization, ranging from narrow rims to areas involving the whole pellet. These contain numerous unfilled vesicles, secondary calcite not being developed. Olivine is present as irregular grains and subhedral to euhedral crystals, the largest measuring 1 mm. in diameter. It is clearer than usual with few inclusions of magnetite and glass.

No. 880. Palagonite tuff from deep ravine due south of summit of Koko Crater. No. 880 is composed of a very vesicular, strongly palagonitized glass contains numerous spherules (glass sulphur yellow, Ridgway 25 f; palagonite orange yellow, Ridgway 17 to 19). Some of the vesicles are partially filled with secondary calcite, occasionally with a low index, low doubly refracting unidentified spherulitic material. Some of the pellets are basaltic, containing chiefly feldspar, augite, and olivine. The interstices are largely filled with secondary calcite and the indefinite spherulitic material. Olivine is included in the palagonite and occasionally occurs as isolated grains in the secondary calcite. It contains inclusions of glass and magnetite. (See Pl. XIX, *F*.)

No. 1852. Palagonite tuff from block of old tuff embedded in new tuff near gap north of Koko Crater (Pl. XX, *A*). No. 1852 is composed of rather widely separated pellets of glass of two kinds, one a brownish black variety containing a large amount of magnetite and the other a yellow to greenish yellow glass (Ridgway 26'b) with little magnetite. The tawny portions are slightly polarizing. The pellets contain inclusions of olivine and shredlike feldspar, showing carlsbad and albite twinning, symmetrical extinction 20°, hence andesine. Olivine is rather abundant containing inclusions of glass, the largest grains measuring 1 mm. In addition to these inclusions the pellets show numerous vesicles. No calcite was noted.

No. 1920. Palagonite tuff from deep ravine south of summit of Koko Crater (Pls. XX, *B, C*). No. 1920 is composed of pellets of clear glass (Ridgway 25'd) slightly palagonitized up to 1 mm. in diameter; the interstices are filled with secondary

calcite and small grains of strongly palagonitized glass. The clearer portions are filled with numerous vesicles up to 0.09 mm. in diameter usually rimmed with palagonite. Some of the vesicles are filled with calcite, others with the unidentified mineral thought to be a form of silica. Olivine of the usual appearance occurs not very abundantly and shows inclusions of glass. Magnetite is rather abundantly developed as euhedral to anhedral grains included in the olivine and the glass. Some of the glass is rendered black by it. Secondary calcite occurs as irregular patches in the interstices and as fillings in the vesicles; many of the vesicles are empty.

No. 3002. Palagonite tuff from south coast of Manana Island (Pl. XXII, *A*). No. 3002 is composed of detached irregular pellets of palagonitized glass, the interstitial spaces partially filled with a spherulitic low doubly refracting, moderate index mineral. The glass contains numerous inclusions of mellilite?, olivine and magnetite. Mellilite? occurs as lath-shaped crystals, the sides regular, the ends irregular, averaging 0.2 mm. by .05 mm. It has a low double refraction and moderate index of refraction. Olivine is of the usual form and size, anhedral to subhedral grains that average 0.3 mm. in diameter, included in the glass. Spherulitic material occurs as circular bodies in the glass averaging 0.2 mm. in diameter and as irregular masses in the interstices, some 0.5 mm. in diameter. It exhibits irregular to circular extinction, low first order gray under crossed nicols, index below balsam. Magnetite is very abundantly developed, blackening part of the glass.

No. 3001. Palagonite tuff from south coast of Manana Island (Pl. XX, *D*). No. 3001 is similar to No. 3002, except that it is less vesicular. It is a palagonitized glass containing numerous inclusions of olivine, mellilite?, magnetite and spherulitic calcite. There are some reef fragments containing foraminifera, the largest measuring 3 mm. in diameter. Mellilite? is more abundant than in No. 3002, occurring as euhedral lath-shaped crystals. Olivine occurs as irregular grain, some reaching a length of 1.5 mm.

No. 2004. Palagonite tuff from sea cliff on east side of Ulupau Head (Pl. XX, *E*). No. 2004 is composed of palagonite pellets, many blackened with magnetite inclusions together with interstitial clouded glass and secondary calcite. The palagonite occurs as grains and pellets that average 0.5 mm. in diameter, orange yellow to yellowish brown color, with slight polarization. Most of the pellets show numerous olivine and globular inclusions, some distinctly spherulitic. Some pellets contain a large amount of magnetite. Olivine occurs as irregular grains in the palagonite, much of it partially absorbed. Many grains are surrounded by and contain inclusions of magnetite. The interstitial glass is clouded, isotropic and in places spherulitic. Secondary calcite occupies about half the interstitial space and frequent exhibits zonal growth. Many of the globular inclusions show concentric rings, some are spherulitic, others show only incipient mineralization.

Discussion of Megascopic and Microscopic Features

INTRODUCTION

The general primary structure of the tuffs of southeast Oahu is that of sedimentary rocks. Most specimens resemble a sandstone of well-rounded grains, except that the round pellets of which the tuff is composed are widely spaced and commonly there is no contact between adjacent pellets. A few specimens examined in thin section are composed largely of broken shards of glass and derived palagonite and contain but few round pellets. The spaces between the glass or palagonite pellets or other fragments are

in a few specimens almost completely filled with secondary calcite while in most of the specimens considerable unfilled interstitial space remains.

Pellets of palagonite, a centimeter or more in diameter, occur in some beds of tuff, but the great bulk of the material has a coarseness of not more than 1 to 2 mm. Most fragments larger than a centimeter in diameter have cooled so slowly as to become crystalline basalt rather than glass, but such fragments are rare except in a few beds of agglomeratic tuff at Roundtop and Mauumae craters.

No determinations of mechanical composition of the tuff were made but it is probable that the original compositions were similar to those of the several black ash samples. (See p. 96.)

The pellets of glass and palagonite which make up the mass of the tuff are in the main rather well-rounded, especially in the finer grained material. Samples of the fine black ash show a larger proportion of rounded pellets and a smaller proportion of elongate, twisted, string-like forms than are found in the coarse black ash. Most of the pellets show no sign of squeezing or deformation of any sort after falling, though a few have a well developed flow structure with elongate vesicles. This may indicate that they remained liquid for a time after expulsion but apparently they were not fluid when they reached the ground. The most notable shape characteristic of the pellets as seen in thin section is the presence of great numbers of vesicles, of which some are open at the margins of the pellets and others completely enclosed.

The principal constituents of the tuffs are glass and palagonite pellets, olivine phenocrysts, magnetite, several accessory minerals, and secondary calcite.

GLASS AND PALAGONITE PELLETS

None of the Oahuan tuffs are so altered as not to contain small quantities of clear, basaltic glass. In a few specimens examined such glass is chiefly confined to inclusions in the larger olivine crystals. In others, notably certain samples from the Koko district, the larger part of the rock is made of unaltered glass, though a sufficient amount of palagonitization has taken place to produce the characteristic bright buff color of these tuffs. The basaltic glass is commonly clear and of light green color (Ridgway 25b). In some specimens it is cloudy with flow line structure and ranges to dark brown or nearly black. In the light green, clear specimens, the extinction is nearly perfect between crossed nicols; the cloudy grains, though darker, extinguish less perfectly. The glass has been affected by two types of alteration, the formation of palagonite and a process of devitri-

fication which has produced clusters of needle-like crystals of an unidentified mineral scattered through its mass.

Palagonite is generally described [28] as a yellowish, brownish, or greenish material derived from basaltic glass by hydration and perhaps oxidation; a process of devitrification. The chemistry of this alteration is not understood in detail. Rosenbusch [29] gives the following analyses:

ANALYSES OF PALAGONITE

	1	2	3	4	5	6	7
SiO_2	44.35	41.03	49.67	40.12	38.96	38.07	36.97
Al_2O_3	13.14	10.77	14.46	13.27	11.62	13.03	7.79
Fe_2O_3	22.88	21.47	18.52	10.65	14.75	9.99	21.02
MgO	4.07	3.79	3.74	3.32	6.29	6.58	4.82
CaO	8.44	6.86	7.23	9.47	9.13	7.54	5.31
Na_2O	2.19	1.64	2.92	2.06	0.68	0.70	7.23
K_2O	0.70	1.09	1.64	0.97	0.72	0.95	0.94
H_2O	4.23	13.55	1.77	20.43	17.85	23.14	15.92
	100.00	100.20	99.35	100.29	100.00	100.00	100.00

1. Sideromelan. Vidoe near Iceland. Bright grains in the palagonite of analysis 2.
2. Palagonite. Vidoe near Iceland.
3. Siderometan. Easter Island.
4. Palagonite. Easter Island contains some sideromelan and zeolites.
5. Palagonite. Seljadalr, Iceland (insoluble residue 4.11 per cent).
6. Palagonite. Galapagos Islands (insoluble residue 0.96 per cent).
7. Palagonite. Aci Castello, Sicily (insoluble residue 6.65 per cent).

According to Rosenbusch and as shown by the analyses, the original basaltic glass (Sideromelan) which may contain some water or be nearly anhydrous, is altered into an extremely hydrous, partly amorphous, and partly crypto-crystalline substance which is known as palagonite from a locality in Sicily. It was first described by von Waltershausen [30]. The palagonite of the Oahuan tuff conforms closely to the few brief descriptions found in the literature. The basaltic glass in general shows a complete extinction between crossed nicols when fresh; and on alteration to palagonite, the extinction becomes less perfect. Some of the palagonite shows fairly definite extinction but most of it is very little changed in doubly polarized light, retaining its bright yellow or red color throughout. No resolvable anisotropic detail was found under the microscope in any pala-

[28] Geikie, A., Textbook of geology, vol. 1, p. 175, 236, 1903.
Kemp, J. F., Handbook of rocks, p. 240, 1921.
Hatch, F. H., Textbook of petrology, p. 65, 271, 1909.

[29] Rosenbusch, H., Elemente der Gesteinslehre, 3 Aufl., p. 406-407, 1910.

[30] von Waltershausen, S., Ueber die vulkanischen gesteine in Sicilien und Island, pp. 179, 424, 1853.

gonite of the tuffs examined. No satisfactory determinations of physical properties of the palagonite were made. It is probable that these are highly variable. A few rough measures indicate a range in density from 1.9 to 2.1. The mean density of the grains of material composing most of the tuffs is higher than this (average about 2.55) due to the presence of much glass, olivine, magnetite and occasional grains of augite.

The palagonite of the Oahuan tuffs is mainly of red-brown color (Ridgway 15 to 21). In a few specimens which are less altered it is bright yellow orange, but little darker than the olive green of the unaltered glass. The alteration first affects the peripheral parts of the pellets and angular fragments of glass, and the margins of vesicles and cracks adjacent to olivine crystals. In some specimens it appears as a sharply defined surface change; in others, particularly those with many vesicles and included mineral fragments, the alteration is more general and less sharply defined, though not necessarily more complete.

Field relations of the palagonitized tuff to the less altered black ash beds are such as to confirm the general belief that the alteration to palagonite is largely hydration. The most altered beds are those which have been relatively less well drained than the more permeable layers and which are fine grained and thus presenting a larger area of grain surface to alteration. The Koko tuffs are generally exceptionally fresh, composed of large quantities of very slightly altered glass surrounded by bright, light orange or orange-red palagonite. In some of these the distinct alteration of glass to palagonite has not penetrated more than two- or three-hundredths of a millimeter and has affected chiefly the grains under one-tenth millimeter in diameter. The Diamond Head and Punchbowl tuffs are much more completely palagonitized but still show considerable amounts of fairly fresh glass. The palagonite of these specimens is commonly bright red-brown in color. The Punchbowl tuff is notable for the small size and exceptional uniformity of the vesicles contained in the glass-palagonite pellets. The Salt Lake tuff is largely in the form of very dark gray, nearly opaque palagonite which has been more generally cemented by calcite than that of any other crater group. A single specimen of tuff from Ulupau shows in thin section a degree of alteration of the glass similar to the Diamond Head tuff and is very thoroughly cemented with secondary calcite.

OTHER CONSTITUENTS

Euhedral olivine occurs in considerable abundance in every specimen of tuff examined and ranges from a fraction of a millimeter to two millimeters in the thin sections. Some of the glass pellets consist of a

small coating of glass surrounding a large olivine crystal, others carry smaller olivine crystals, still others are wholly free from olivine. The olivines show mainly crystal outlines but a few have pitted and rounded margins which suggest that they were corroded in the magma before expulsion. Round or elongate inclusions of clear to somewhat cloudy basaltic glass are common in the olivine crystals and practically all contain grains of magnetite, in part euhedral. In the amount of olivine, the individual specimens of tuff show a moderate variation, no characteristic difference in this respect being noted between the tuffs of the several crater groups.

Small euhedral grains and occasional larger masses of magnetite are as universally present as olivine. They are included in the olivine crystals, in the laths of plagioclase where these occur, and in the glass-palagonite pellets. The magnetite crystallized in part prior to the olivine but continued to form after most of the olivine was crystallized, since the larger masses of magnetite are commonly peripheral to crystals of the latter. Square sections of octahedrons are moderately common but much of the magnetite is in rude grains without geometric form.

Laths of plagioclase are present in a few thin sections examined under the microscope but are missing from most of the tuff. Nepheline and mellilite were found in certain specimens. Fragments of reef rock and the calcareous parts such organisms as mollusks, foraminifera, and corals, appear in nearly all the tuff but are especially abundant in the material from Manana Island, Ulupau Head, and parts of Diamond Head.

BOMBS

Large masses of basalt were thrown out with the ash of nearly every crater, but special petrographic interest attaches to the dense segregation or heavy bombs which occur in all the tuffs but are particularly abundant at Salt Lake. Two of these are described as follows:

No. 641C. Peridotite bomb from east rim of Aliamanu crater. No. 641C has a granular holocrystalline texture, the minerals in the order of abundance being augite, olivine, enstatite, garnet, magnetite, and biotite. Augite, the predominant mineral, comprises about three-fourths of the slide and occurs as subhedral to anhedral grains that average about 1 mm. in diameter. Many of the crystals show numerous parallel striations, suggesting diallage. It is comparatively unaltered and contains inclusions of brown biotite, magnetite and garnet. Enstatite is sparingly developed, the largest crystals measuring 0.5 mm. in diameter and is distinguished from augite by its low double refraction and parallel extinction. Olivine is rather sparingly developed chiefly as anhedral crystals, the largest crystals measuring 1 mm. in diameter, and is unaltered and intergrown with augite. Garnet is rather abundant occurring as light pink equidimensional grains that show strong fracture cracks along which magnetite is usually developed, some of the grains measure 0.5 mm. in diameter. Magnetite occurs as euhedral to subhedral grains the largest 0.1 mm. in diameter and is included in the other minerals. Biotite occurs very sparingly

as deeply pleochroic brown shreds not over 0.1 mm. long included chiefly in the augite and to a less extent in the olivine. One piece of palagonite was noted in the interstitial spaces.

No. 1020. Olivine rock (dunite) from northwest shore of Salt Lake. No. 1020 is a coarsely crystalline rock made up almost entirely of olivine with enstatite, serpentine, biotite, magnetite, spinel, and titantite, sparingly developed. Olivine occurs as subhedral to anhedral grains 1.5 to 2 mm. in diameter comparatively fresh and with iron inclusions. It shows a slight alteration along cleavage cracks to serpentine. Enstatite is very sparingly developed as subhedral grains not more than 0.5 mm. long. A deep brown strongly pleochroic biotite is sparingly present. Titanite also occurs sparingly along the cleavage cracks of olivine as oval shaped strongly fractured grains that measure 0.4 mm. in diameter. Only one fragment of spinel was noted. It appears as irregular grains of reddish brown color, high index of refraction and isotropic, and is probably the variety picotite. Magnetite developed as inclusions in the olivine is rare. These bombs range up to 5 inches or more in diameter and are the principal source of some of the heavy minerals identified in the detrital sediments.

SEDIMENTARY ROCKS

The specimens of sedimentary rock studied constitute a representative series of the fluvial and marine derivatives which surround the pyroclastic craters. They show an exceptional abundance of euhedral mineral grains due in part to the habit of the characteristic minerals present but in part to the mode of pyroclastic expulsion which favors the preservation of crystal form.

Alluvial Sediments

No. 81. Sand from small channel on west slope of Diamond Head. No. 81 is a moderately well sorted medium sand of which 43% falls in the 1/4-1/2 mm. grade (fig. 27, *a*). The sand as a whole consists preponderantly of tuff fragments, which are rough and angular. Grades below 1/2 mm. contain considerable amounts of olivine, mostly in euhedral grains. Small quantities of secondary calcite are present. A few small grains of leucite were identified in the 1/8-1/16 mm. grade. The 2.73 density separate consists of tuff fragments and a few pieces of secondary calcite. In the minus 2.73 separate are mainly euhedral olivine grains with an occasional small magnetite fragment.

No. 496. Fine grained alluvium from east of Kaimuki crater. No. 496 is a fine grained red-brown baked silty clay, substantially a laterite. On washing the material a very few particles of 1/16 to 1/4 mm. magnetite grains are found, the remainder consisting probably mainly of limonite.

No. 664B. Rill concentrate sands from north inner slope of Salt Lake crater (fig. 27, *b*). No. 664B is composed of rudely assorted angular grains from 1/8 to 8 mm. in diameter, no grade exceeding 30%, and four being over 15% in amount (fig. 27, *b*). Very little density sorting is evident, the coarser grades containing olivine, augite and basalt as well as tuff fragments and fragments of shells. In the finer grades several other minerals are present. The material is derived largely from the crumbling of the heavy mineral bombs which are so conspicuous in the Salt Lake tuff. The finest grade consists largely of broken tuff fragments and small magnetite filled aggregates. The minus 2.73 separates consists of porous gray tuff. The 2.73-

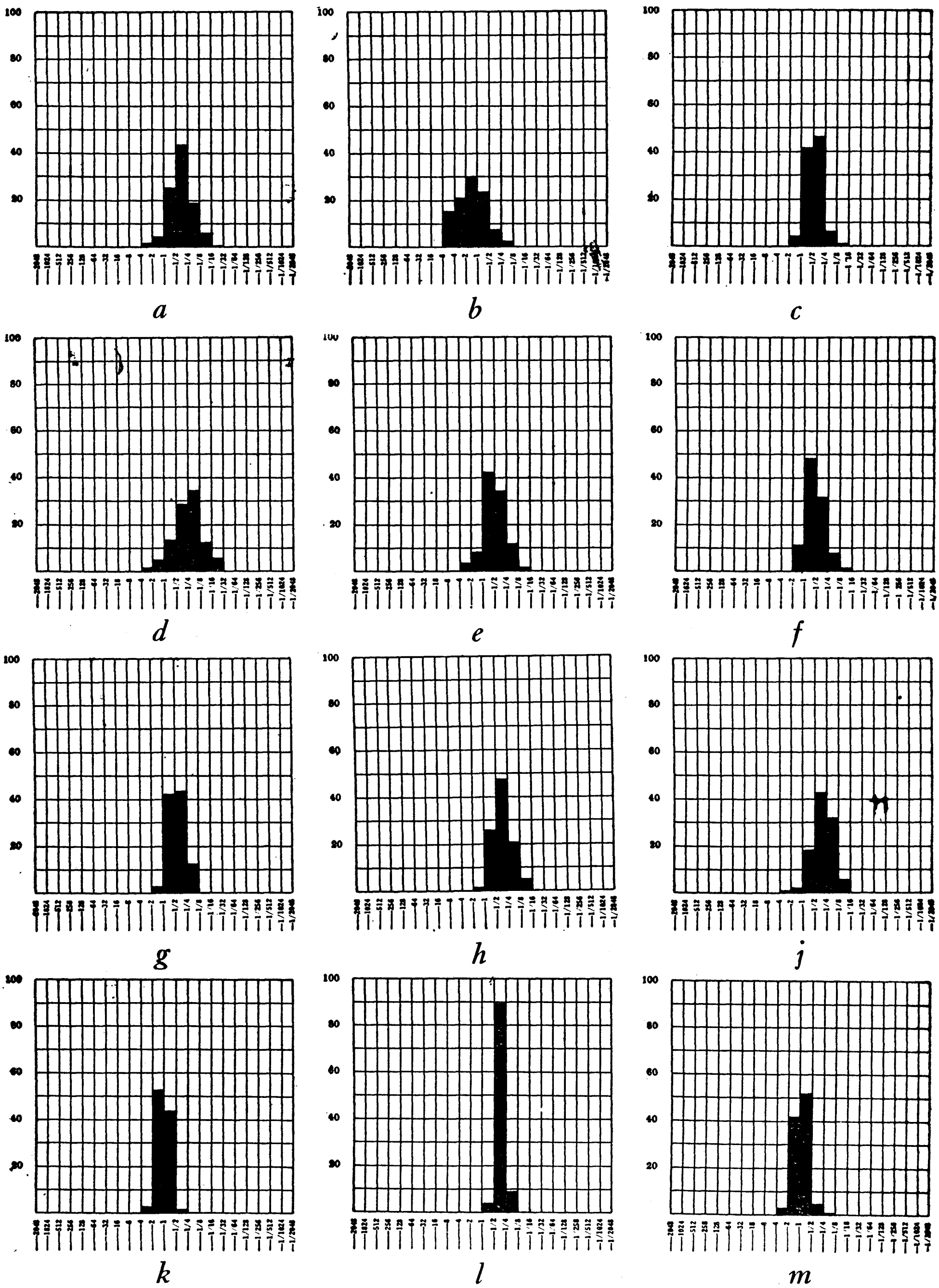


FIGURE 27.—Diagrams showing mechanical composition of stream sands, beach sands and sand concentrate: *a,* No. 81, sand from small channel on Diamond Head slope; *b,* No. 664B, sand from rill channel on Salt Lake Crater slope; *c,* No. 796, sand concentrate from ant hill on Salt Lake shore; *d,* No. 523, sand concentrate from Tantalus Road; *e,* No. 120, sand concentrate in channel on Koko Head; *f,* No. 841B, sand from channel on Koko Crater; *g,* No. 1821, sand from stream channel on Koko Crater; *h,* No. 1859, sand from channel on Koko Crater; *j,* No. 1860, sand from channel on Koko Crater; *k,* No. 12, beach sand from near Diamond Head; *l,* No. 21B, olivine sand from Diamond Head beach; *m,* No. 610, beach sand from near Kupikipikio Point.

Figures at the right indicate percentages; figures at the bottom indicate grade sizes in millimeters; numbers refer to samples described in the text.

3.36 separate consists of olivine and aggregates carrying olivine, magnetite and glass. The plus 3.36 separate consists of magnetite and garnet (pyrope).

No. 796. Sand concentrate from ant hill, Salt Lake shore (fig. 27, *c*). No. 796 is mainly a beach sand reselected by ants; 88% of its grains or ¼ to 1 mm. in diameter. A few olivine augite grains are found in the 2-1 mm. grade which is mainly tuff and basalt. In the finer grades are augite, olivine, and garnet. Less than 10% of this sand has a density under 2.71, 16% is from 2.71 to 3.14, 66% from 3.14 to 3.37 and 7% over 3.37, the latter mostly magnetite and garnet.

No. 523. Plunge pool concentrate from ridge road to Tantalus (fig. 27, *d*). No. 523 is a moderately well sorted sand with 34% in the 1/8 to 1/4 mm. grade. The plus 1 mm. grades consist of weathered fragments of black ash and tuff. The finer grades are composed increasingly of olivine and especially of magnetite grains, of which the smaller are almost wholly euhedral. The minus 2.73 separate is mainly tuff and calcite, the 2.73-3.14 separate chiefly composite grains, the 3.14-3.36 mostly olivine and the plus 3.36 largely euhedral magnetite 0.1-.05 in diameter and small garnets. Ten per cent of this sand is under 2.71 density, 17½% is 2.71-3.14, 68% is 3.14-3.36 and 4% over 3.36.

No. 120. Pothole concentrate of sand on west flank of Koko Head (fig. 27, *e*). No. 120 is rather coarse sand. Tuff and basalt fragments make up the bulk of the 4-2 mm. material, euhedral olivine appears in the 2-1 mm. grade and becomes dominant in all grades below 1 mm. Magnetite is found in all grades under 1/4 mm. A few rounded grains of leucite are found in the 1/6-1/8 mm. grade, 69% of the sand is over 2.73 in density, being predominantly olivine.

No. 841B. Slightly transported alluvium from west flank of Koko Crater (figs. 26, *l* and 27 *f*). No. 841B is the result of slight transportation of the black ash found at the same locality, together with detritus from higher up the Koko slope and shows the selective action of running water. The coarser grades consist mainly of tuff pellets with battered grains of black glass. In the finer grades olivine is abundant as euhedral forms encrusted with palagonite and secondary calcite from the tuff. Very little if any magnetite appears in the fine grades. About 63% of the material has a density over 2.73.

No. 1821. Channel sand from west flank, Koko Crater (fig. 27, *g*). No. 1821 is a medium to coarse, moderately well sorted sand and consists largely of tuff encrusted olivine crystals. The 1/4 to 1 mm. grades carry especially well-formed and little abraded crystals. More than 83% of this sand is over density 2.73, largely olivine but also magnetite-loaded glass and tuff fragments.

No. 1859. Channel sand near road on northeast slope of Koko Crater (fig. 27, *h*). No. 1859 is a medium sand consisting very largely of olivine with small quantities of glass and tuff. Nearly 75% has a density over 2.73.

No. 1860. Sand from a large channel on northeast slope of Koko Crater (fig. 27, *j*). No. 1860 is similar in composition to No. 1859 and carries 81% of density over 2.73. In the 1/2-1 mm. grade of this specimen a well preserved gastropod shell was noted. Whether this has been preserved since the eruption took place beneath sea level or whether it is of accidental eolian transport from the present coast is not known.

Beach Sediments

No. 12. Beach sand south of Diamond Head (fig. 27, *k*). No. 12 is a well sorted coarse sand of which 96% falls in the two grades 1/2-2 mm. The coarser grades are chiefly calcareous organic debris with subordinate tuff fragments. Olivine crystals constitute probably less than 1/100 part of the plus 2.73 separate, which in turn constitutes 4% of the whole mass. The plus 2.73 separate consists chiefly of certain organic materials of high density.

No. 21B. Olivine beach sand southeast of Diamond Head (fig. 27, *l*). No. 21B is a very well sorted medium sand of which 89% falls in the 1/4-1/2

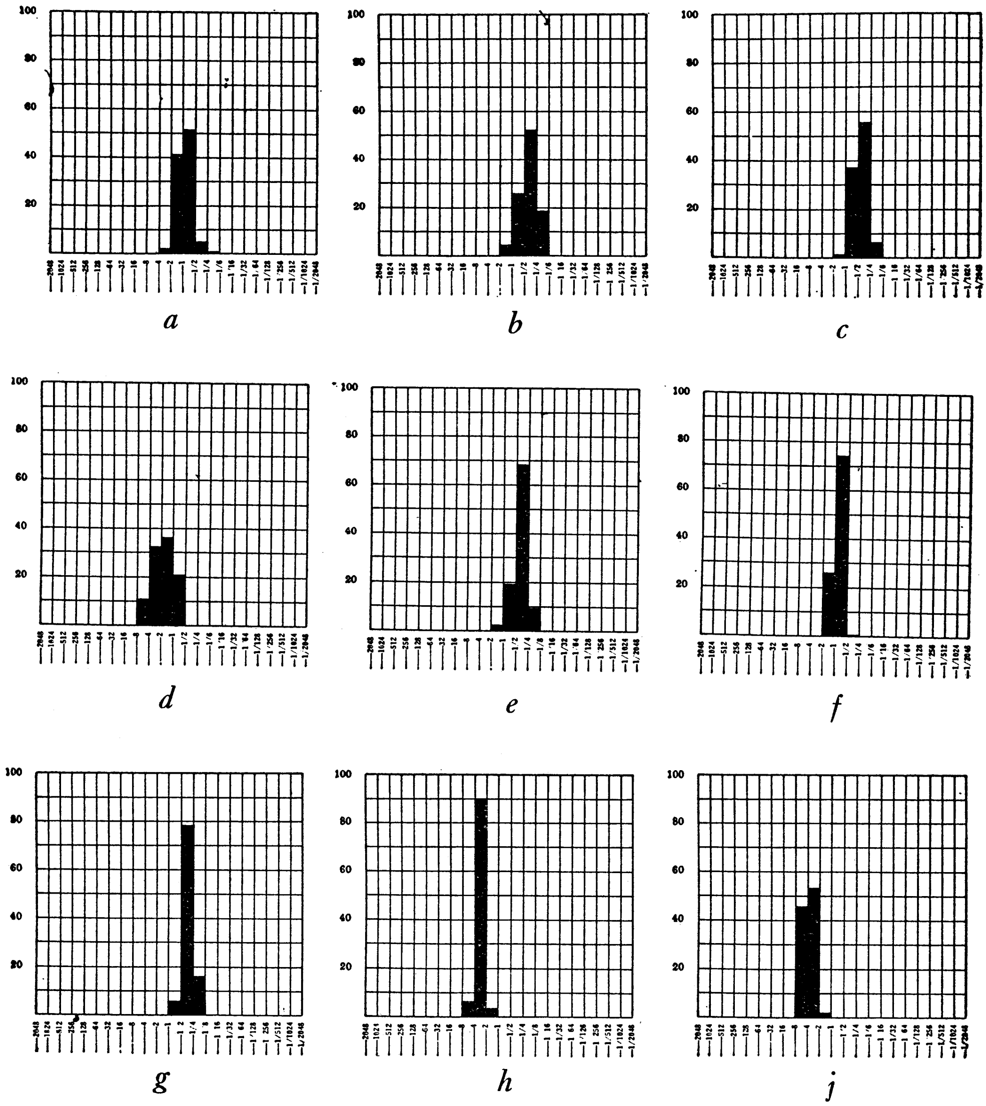


FIGURE 28.—Diagrams showing mechanical composition of beach sands and gravels: No. 611, beach sand from Kupikipikio Point; *b*, No. 1021, beach sand from Salt Lake Shore; *c*, No. 130, beach sand from Koko Head shore; *d*, No. 740D, sand concentrate from bench on Hanauma Bay shore; *e*, No. 1302, beach sand from Koko Crater beach; *f*, No. 1885, beach sand from west of Makapuu; *g*, No. 1886, beach sand from west of Makapuu; *h*, No. 1887, crystal sand from south of Koko Crater; *j*, No. 1933, gravel from Koko Crater beach. Figures at the right indicate percentages; figures at the bottom indicate grade sizes in millimeters; numbers refer to samples described in the text.

mm. grade and 99% is of density over 2.73. Most of the olivine which is almost the sole constituent of this sand is in sharp-edged euhedral grains showing gas bubbles, glass inclusion and included euhedral magnetite. A small fraction, about 1/2%, of the olivine grains, are notably battered and rounded so as to almost wholly obscure their crystalline form.

No. 610. Beach sand west of Kupikipikio Point (fig. 27, *m*). A coarse calcareous sand containing small quantities of olivine (6% density over 2.73; much of this organic fragments) but consisting mainly of molluscan shells, tests of foraminifera and similar fragments.

No. 611. Olivine beach sand from west of Kupikipikio Point (fig. 28, *a*). No. 611 is a fine sand of which more than 99% is between 1/8 and 1/2 mm. Grains above 1/2 mm. consist of calcareous shell fragments with a few olivine crystals. The 1/16-1/8 grade consists of perhaps 10% magnetite, largely in octahedrons, and the remainder euhedral olivine. Over 98% of the whole sand and practically all of the middle size grades have densities between 2.73 and 3.36 and consist of olivine. A few of the magnetite and olivine grains are much battered but most are sharp edged crystals.

No. 1021. Beach sand from Salt Lake shore (fig. 28, *b*). No. 1021 is a fine sand with an unusual assemblage of heavy minerals. Less than 12% lies in the minus 2.73 separate, 83% in the 2.73-3.36 separate and 5% has densities over 3.36. The coarser grades consist of olivine, tuff, augite, glass and garnet. The finer grade is composed largely of small magnetite bearing tuff fragments and olivine crystals with less amounts of garnet, and black glass. In the medium grades olivine, augite and glass are conspicuous and garnet and tuff magnetite aggregates are present. The minus 2.73 separate is mainly tuff. The plus 3.36 separate consists chiefly of garnet, magnetite and ilmenite.

No. 130. Beach sand from west shore of Koko Head (fig. 28, *c*). No. 130 is an olivine sand carrying slightly more than 1% of grains under 2.73 density. It is well sorted, about 93% falling in the 1/4-1 mm. range. The plus 1 mm. grade consists mainly of calcareous shell and tuff fragments. The intermediate grades consist wholly of euhedral olivine, of which a few grains are somewhat battered and rounded but most are sharp edged and unabraded. The finer grades are similar. No magnetite was seen in the plus 2.73 separate which is 100% olivine.

No. 740D. Spray pool concentrate on Hanauma Bay coast (fig. 28, *d*). No. 740D is a sand poorly sorted as to size but which carries an unusual proportion of olivine and augite crystals. The 8 to 2 mm. grades consist of tuff, basalt, and shell fragments. Nearly one half of the euhedral olivine and a few augite crystals appear in the plus 1 grade. In the plus 1/2 mm. grade most of the tuff, basalt and shell fragments are missing and the olivine comprises nearly the whole of the grade, augite crystals being present but rare. A few euhedral augites are present in the plus 2.73 separate but nearly the whole of this is olivine.

No. 1302. Beach sand Koko Crater shore (fig. 28, *e*). No. 1302 is a mixed moderately well sorted sand (fig. 28, *e*). The plus 1 grade consists nearly all of shell fragments and subordinate tuff and basalt fragments. The plus 1/2 grade consists of nearly equal amount of euhedral olivine and shell fragments and formaminifera. In the plus 1/4 grade the olivine becomes subordinate. The plus 2.73 separate comprises nearly 40% of the whole and is chiefly olivine with a few heavy organic fragments.

No. 1885. Beach sand from north shore Oahu west of Makapuu Head (fig. 28, *f*). No. 1885 is a coarse sand falling chiefly in the 1/2 to 2 mm. range. The plus 1 mm. grade consists wholly of calcareous organic detritus. Very small quantities of tuff and olivine are found in the plus 1/2 grade and magnetite laden olivine grains in the plus 2.73 separate which comprises about 16% of the whole and is mainly heavy shell material.

No. 1886. Mixed beach sand from north shore west of Makapuu (fig. 28, *g*). No. 1886 is a very well sorted sand of which 80% falls in the 1/4-1/2 mm. grade. About 60% is over 2.73 in density. The coarser grades carry equal amounts of olivine crystals and organic detritus, all very clean and brightly polished. The 1/8 grade is mainly very clean euhedral olivine with a few grains of magnetite. The plus 2.73 material is mainly olivine with small amounts of heavy shell debris and magnetite.

No. 1887. Coarse sand from Koko Crater beach (fig. 28, *h*). No. 1887 consists of shell fragments and gray basalt fragments 1 to 8 mm. in diameter.

No. 1933. Beach gravel from Koko Crater beach (fig. 28, *j*). No. 1933 is a well assorted gravel mixture of basalt fragments (mostly dapilli from tuff) and shells. Coral and algae fragments, small gastropods and sea urchin spines are the chief organic constituents.

No. 1987. Crystal gravel from near Kahaulou crater (Pl. XXI, *C*). No. 1987 consists of euhedral augites 1 to 8 mm. in diameter. These crystals and crystal clusters are strewn on parts of the surface west of Kahaulou and are concentrated by rills down the slopes. The presence of these clean, sharp crystals thrown out during one of the later eruptions suggests that large quantities of augite and olivine crystals have been thrown out directly to become constituents of modern sediments with no need for intervening weathering.

No. 2027. Beach sand from Ulupau Head. No. 2027 is a moderately well sorted sand and consists practically wholly of foraminifera and molluscan shells. A few olivine crystals are found in the plus 2.73 separate.

Consolidated Sediments

No. 96. Medium calcareous sandstone from Kupikipikio Point (Pl. XX, *F*). No. 96 is a fairly compact, granular rock of light cream color. Numerous olivine crystals can be seen in certain zones in the hand specimen. Under the microscope the rock is seen to have the typical structure of a sandstone, being composed of beautifully rounded calcareous grains with a few somewhat less rounded fragments of mollusk shells, corals, algae, foraminifera and other unidentified marine organisms. The olivine grains include magnetite, glass and palagonite and are accompanied by very rare fragments of basalt and tuff. The grains are well cemented in an almost complete calacareous matrix made up of numerous fibre-like calcite crystals which have grown out into the interstitial spaces in directions normal to surfaces of the grains.

No. 496A. Calcareous sandstone from near Honolulu Construction Co. quarry, Kapahulu Street. No. 469A is a coarse sandstone of similar structure and composition to No. 96. It differs from it in the more complete cementation and in the complexity of recrystallization within the shell fragments. These are regrown in a way to bring out very beautifully the intricate structures of the organic grains.

No. 1149. Calcareous sandstone from the shore of Pearl Harbor. No. 1149 consists of calcareous fragments of foraminifera and other marine organisms in a dark, compact matrix, which is nearly opaque under the microscope. A few olivine crystals are present and several finely granular basalt grains.

No. 1158. Calcareous sandstone from Pearl Harbor shore. No. 1158 is a sandstone similar to No. 1149 but is more firmly cemented in a coarser grained calcareous matrix. Both the organic grains and matrix extinguish in dull grays and show little color between crossed nicols.

No. 847. Calcareous reef rock from block blown up from submarine reef in Kahaulou explosion. No. 847 consists mainly of coral with associated marine organisms cemented into a solid calcareous mass.

SUMMARY OF LATE GEOLOGIC HISTORY OF SOUTHEAST OAHU

For each group of craters on Oahu the sequence of geologic events has been established (pp. 31-91) but the distribution and general similarity of pyroclastic materials prevents direct stratigraphic determination of relative age.

The date of formation of the Koolau Range is not known with reference to the European or American geologic time scales and the assignment by Dall [31] of reef limestones on Oahu to the Tertiary can hardly be regarded as final. Estimates of the age of islands of Hawaii can at present be based only on rough estimates of duration of various physical events.

In an earlier report [32] it was estimated that Lanai experienced "an erosional period of some 100,000 to 150,000 years and a volcanic formative period of perhaps 50,000 years" and that "the first appearance of Lanai above sea level dates from a time well back of the Wisconsin period but not so far back as the early Pleistocene." Data are lacking for a similar estimate of the age of Oahu but certain comparisons may be of value. According to a rough estimate based on the topographic map, about one-third of the leeward slope of the Koolau Range has been cut away by erosion. The average elevation of this part of Oahu is about 1000 feet which corresponds to the remaining two-thirds of the original mass. The amount of material eroded is thus of the order of 500 feet, perhaps twenty times as much as that removed from Lanai. The average initial elevations of the two islands was similar; the greater exposure of Oahu may have given to the leeward Koolau slope as great a rate of erosion as that for both windward and leeward slopes of Lanai.

If it be assumed that the rates of erosion on the two islands have been similar the duration of the erosion of the Koolau Range may be taken as twenty times that of Lanai, that is, 2,500,000 years. When the present rate of growth of the Mauna Loa-Kilauea region is considered, it seems unlikely that this volcanic mass can be less than 100,000 years. The Kohala cone of Hawaii must be many times as old, but even its erosion is slight compared to that of the Koolau Range of Oahu; and the Waianae Mountains are unquestionably very much older than the Koolau Range. In fact, 2,500,000 years seems a low estimate.

[31] Dall, W. H., Notes on the tertiary geology of Oahu, Geol. Soc. Am. Bull. 11, pp. 57-60, 1900.

[32] Wentworth, C. K., The geology of Lanai, B. P. Bishop Mus. Bull. 24, pp. 52-57, 1925.

The elevation of the sea at the time of principal volcanic activity in the Koolau Range is not known. Coral reef formations extend several hundred feet below sea level under parts of Honolulu and it is clear that some time after the Koolau Range was formed and extensively eroded but long prior to present time the sea stood several hundred feet below its present level. These reef formations are interbedded with terrigenous sediments which indicate a very long period of slow encroachment of the sea on the land. All these events took place before the oldest known pyroclastic eruptions. The earliest stage in the physical history of Oahu to which the pyroclastic eruptions can be related is the epoch during which the sea stood about 40 feet higher than its present position. During this stage, which may for convenience be called the Waialae stage, the sea cut a long line of cliffs, 50 to 200 feet high, against the southwest flanks of the Koolau Range, extending from Makapuu Head to Pearl Harbor; and produced similar features round the rest of the Oahu shore, which are preserved now with less continuity. These cliffs rise from the inner margin of a wave-cut bench which is mantled with gravel and coral formations.

No means is at hand for determining the relative age of the Waialae cliff as compared to the Koolau Range itself. However, the complex history which must be postulated for the formation of several hundred feet of coral rocks below present sea level, the large amount of erosion which preceded some of this reef growth, but which followed the main volcanic activity forming the Koolau Range, and the fact that in Waialae time the principal valleys in the Koolau slope were very much as they now are, indicate that the total post-Waialae time must be small compared to the pre-Waialae (but post-Koolau) time. If the assignment of 2,500,000 years to post-Koolau time is valid, post-Waialae time may be of the order of 100,000 or 200,000 years.

Following the Waialae stage was a stage of increased stream competence during which great amounts of gravels were carried out from the mouths of the principal valleys building broad fans graded to the 40 foot level and extending one or two miles seaward of the Waialae cliff line. With continued deposition and following the high gradients of these short, torrential streams, the fans were extended inland to reach elevations of 125 feet or more at their heads. This stage may be called the Fort Shafter stage from the extensive terrace deposits formed at this time.

After the close of the Fort Shafter stage of fan building, the next recognizable stage is that during which the sea stood about 12 feet higher than now and cut the eustatic bench which is prominent on all the islands

of this part of the Pacific as described by Wentworth and Palmer.[33] This bench is well developed around the margins of most of the coastal tuff craters and furnishes a date of some value in correlation. Because this bench is well developed around the margin of Hanauma Bay the stage may be referred to as the Hanauma stage.

Following the development of the Hanauma bench the sea withdrew to its present level and initiated what may be called the modern stage. The duration of post-Hanauma time can only be roughly estimated by the fact that only the most recent volcanic events on Hawaii have occurred since the emergence, whereas the obviously very recent eruptions of the Koko region occurred before the shift. Wentworth and Palmer conclude that the latest Koko tuff formations are not more than 20,000 years old and may not be more than 1,000 years old.

It is believed that the last activity in the Koko region antedates the coming of the Polynesian natives but does not go back to great geological antiquity, both the last eruptions and the eustatic shift being post-Wisconsin in time, occurring perhaps 5,000 years ago.

Diamond Head, Salt Lake, and Ulupau Craters are known to have been active during or before Fort Shafter time, and inconclusive evidence indicates that Punchbowl was formed at this time. It seems probable that neither the Koko vents nor those of the Tantalus-Roundtop group became active until Hanauma time.

The probable order and correlation of events in the pyroclastic history of southeast Oahu may be listed as follows:

1. Close of Koolau Range volcanic activity.
2. Prolonged erosion.
3. Extensive growth of coral reefs and accumulation of interbedded terrigenous sediments during progressive submergence of the land from a position several hundred feet above its present level.
4. Cutting of submarine bench and Waialae cliff while the sea stood forty feet higher than at present.
5. Continued stand of the sea at its forty foot position with increased stream competence and building of Fort Shafter terrace and similar gravel terraces and fans in other parts of Oahu.
6. Eruption of Diamond Head, Salt Lake craters, Ulupau, and Puu Hawaiiloa. Punchbowl eruption probably at this time also.
7. Continued fan building and removal of large parts of the Salt Lake fans by lateral cutting of Moanalua stream. Marine bench and cliff cut into the flank of Diamond Head at the forty foot level. Extensive erosion of Ulupau crater and mantling of inner slopes with tuff gravels. Similar erosion of Diamond Head and Punchbowl.
8. Emergence of Oahu to the twelve foot level and cutting of marine bench.

[33] Wentworth, C. K. and Palmer, H. S., Eustatic bench of islands of the North Pacific, Geol. Soc. Am. Bull., vol. 36, pp. 521-544, 1925.

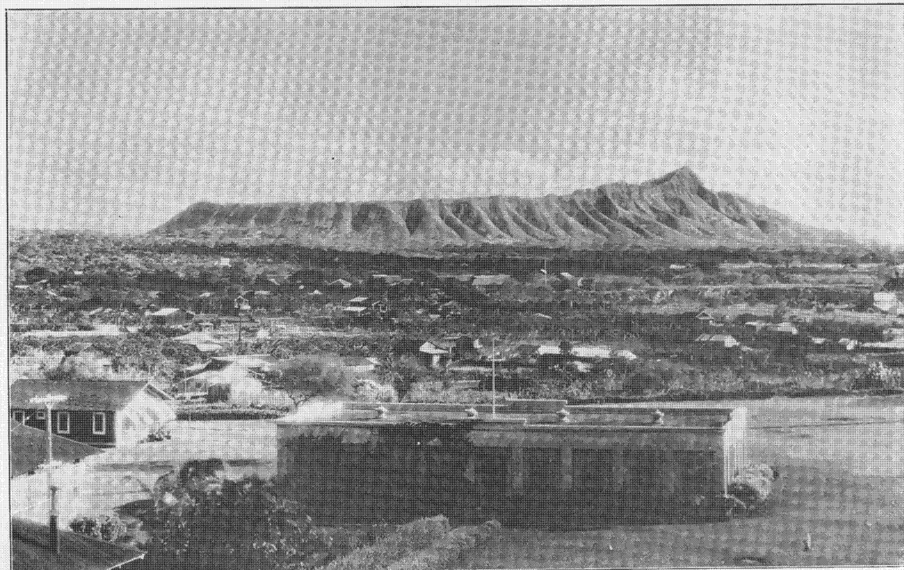
9. Late eruptions of Salt Lake craters. Black ash and basalt flow eruption of Punchbowl and black ash, rhyoclastic, and flow eruptions of the Tantalus-Roundtop-Rocky Hill-Manoa dike series all contemporaneous. Kaimuki, Mauumae, and Kupikipikio eruptions thought to be simultaneous and presumably contemporaneous with the Punchbowl and Tantalus eruptions. Ihiihilauakea (Koko Head vent), Hanauma Bay, and unnamed pre-Koko crater eruptions.
10. Erosion of Koko group and other craters. Cutting of marine bench at the 12-foot level.
11. Hanauma Bay, Koko Crater, and Kalama crater eruptions. The eruptions at Manana and Kaohikaipu islands probably came at this time.
12. Erosion of Koko and others. Recutting of marine bench at the 12-foot level.
13. Kahaulou, Nonoula, and Koko dike eruptions. (Manana and Kaohikaipu eruptions?)
14. Erosion of Koko group and other craters and cutting of marine bench at 12-foot level.
15. Emergence of Oahu to present level and continued erosion of the craters.

This synopsis includes only such separations in time as are clearly indicated by the data. Craters, the relative age of which is not known, are assumed to have erupted at about the same time. Thus the general similarity of the Diamond Head and Punchbowl craters and the fact that they cannot differ widely in time suggests that they were formed nearly simultaneously. Whether the early Salt Lake eruptions and those of Ulupau and Puu Hawaiiloa were also contemporaneous with Diamond Head and Punchbowl is uncertain.

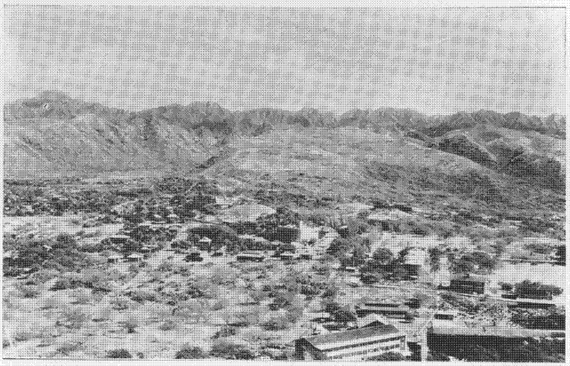
The similarity in composition of the Punchbowl basalt and the basalts of the Rocky Hill-Manoa dike series strongly suggests that these vents were active at the same time; the Punchbowl for the second time; and Rocky Hill-Manoa for the first time. For the same reason, the Puu Hawaiiloa flow eruption is placed within this same period. There is no direct evidence for dating the Kaimuki, Mauumae, and Kupikipikio eruptions with reference to each other, but their relations to the Diamond Head tuff are similar.

The relation of the Koko dike eruptions to Kalama crater has not been established. The basalt of Kalama crater is mantled with tuff which is thought came from the main Koko Crater vent, but the Koko dike lava is closely associated with tuffs very much younger than the main Koko Crater mass. If the material on the rim of Kalama crater is late Kahaulou tuff or if the Manana eruption was as recent as that of Koko dike and the source of the tuff remnant on Kalama crater, the Koko dike flows and Kalama crater might be contemporaneous. With sufficiently detailed field and microscopic studies the relations of the several tuffs and basalts probably could be determined.

Koko crater from the southwest. The foreground shows part of the outer rim of the Hanauma Bay crater. Near the summit may be seen the convergence of heads of ravines from Kuapa Pond on the west and from the ocean on the south.



Diamond head crater from the campus of the University of Hawaii. The high summit at the right, 761 feet above sea level, is due to preponderant accumulation under the influence of trade wind drift.



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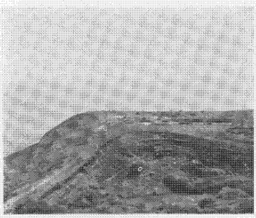

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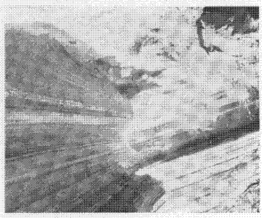
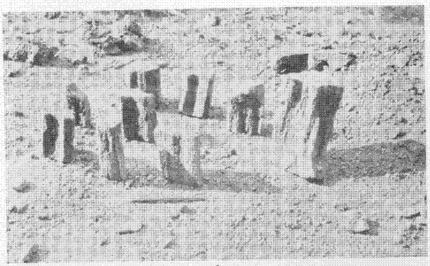


C

A, KOOLAU RANGE FROM DIAMOND HEAD. THE BROAD, TABULAR SLOPE IN THE MIDDLE DISTANCE IS THE FLOW SLOPE FACET EAST OF MANOA VALLEY. THE RUGGED, DECLIVITOUS CREST OF THE RANGE FORMS THE SKYLINE. *B*, RIM CREST SOUTHEAST OF KOKO HEAD SHOWING ANTICLINAL STRUCTURE OF TUFF FORMED BY PROGRESSIVE MANTLING ALONG LINE OF MORE RAPID ACCUMULATION OF ASH. *C*, TUFF BEDDING IN WALL OF EXPLOSION CRATER EAST OF KOKO HEAD. NOTE THE EXCEPTIONAL UNIFORMITY OF THE STRATIFICATION COMBINED WITH THE LACK OF DISTINCT BEDS.



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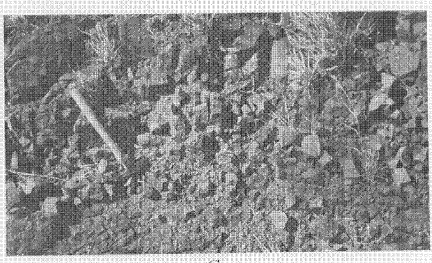
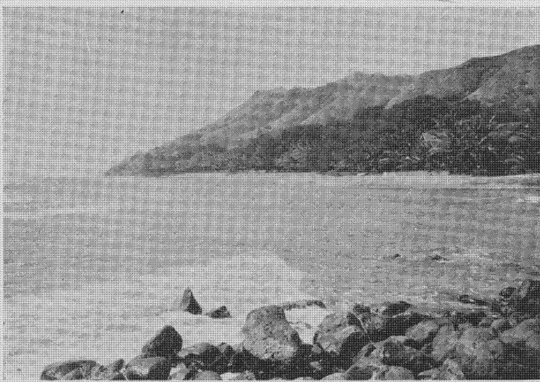


C

A, RUDE POLYHEDRAL BLOCKS OF DIAMOND HEAD TUFF PRODUCED IN THE SURFACE LAYERS BY BAKING FROM HEAT OF SUPERPOSED KAIMUKI BASALT. *B*, POLYHEDRAL BLOCKS OF TUFF PRODUCED BY SUB-SPHEROIDAL WEATHERING; ROAD CUT SOUTHEAST SIDE OF SALT LAKE CRATER. *C*, WEATHERED SURFACE OF TUFF SHOWING CHARACTERISTIC SMALL BLOCKS PRODUCED BY WEATHERING IN DRIER SITUATIONS; DIAMOND HEAD RIM NORTH OF SUMMIT PEAK.

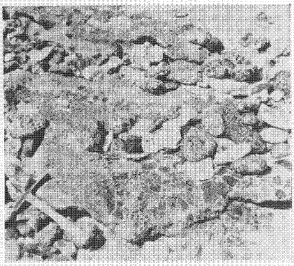
A

B



C

A, VIEW OUTWARD FROM NARROW RAVINE CUT IN TUFF ON THE WEST FLANK OF DIAMOND HEAD. *B*, POTHOLES CUT IN TUFF IN RAVINE ON WEST SLOPE OF KOKO CRATER. *C*, DIAMOND HEAD FROM KUPIKIPIKIO POINT.



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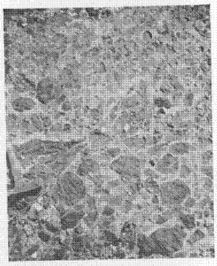

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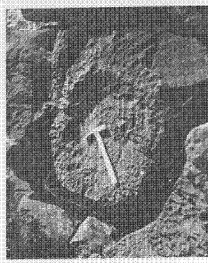
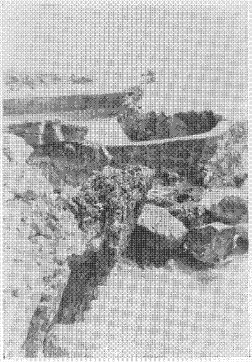


D

A, breccia in place and as cobbles, composed mainly of angular fragments of tuff in a calcareous matrix on the wave-cut bench, seaward face of Diamond Head. *B*, talus breccia composed of tuff fragments in a calcareous matrix, north flank of Diamond Head. *C*, boulders of Kupikipikio basalt at south end of Kupikipikio point. *D*, basalt block on southwest slope of Kaimuki crater showing rude polyhedral form produced in the cooling of the basalt flows.



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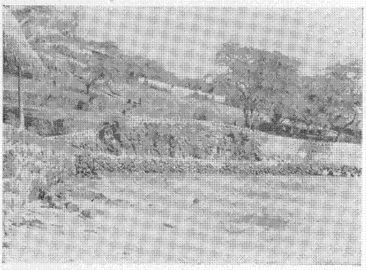
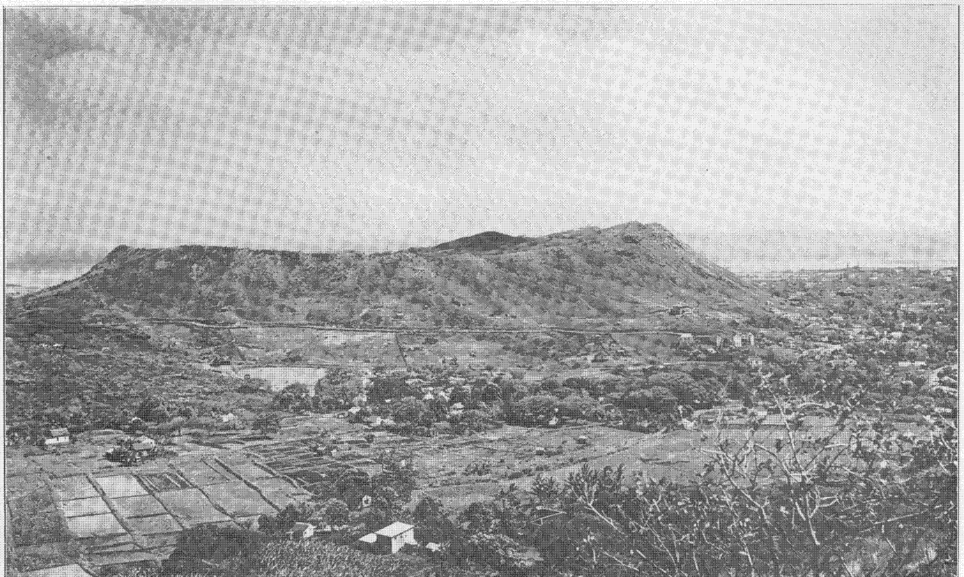


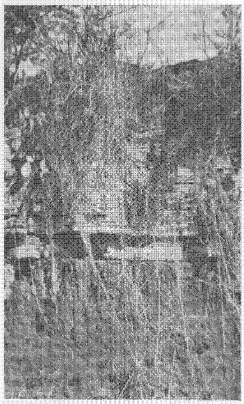
C

A, EXTREMITY OF KUPIKIPIKIO DIKE CUTTING REEF LIMESTONE AND UTILIZED AS PART OF THE WALL OF A FISH POND. *B*, KAIMUKI BASALT OVERLYING DIAMOND HEAD TUFF IN QUARRY OF HONOLULU CONSTRUCTION CO., KAPAHULU STREET. *C*, SOUTHWEST END OF KUPIKIPIKIO DIKE, WEST SIDE OF KUPIKIPIKIO POINT.



Punchbowl, from the north. (Photograph by Perkins.)

A



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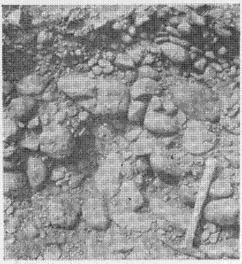

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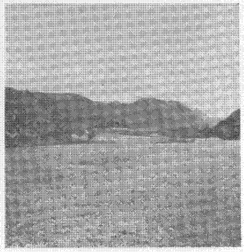
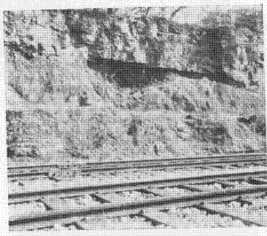


D

A, FORT SHAFTER GRAVEL OVERLYING FINER GRAINED TUFFACEOUS ALLUVIUM IN BLUFF OVERLOOKING MOANALUA GARDENS FROM THE EAST. *B*, SALT LAKE TUFF OVERLYING OLD SOIL SURFACE IN ROAD CUT WEST OF RED HILL. (PHOTOGRAPH BY H. S. PALMER.) *C*, FORT SHAFTER GRAVEL IN ROAD CUT EAST OF AIEA. *D*, BROAD FLAT OF MOANALUA VALLEY UPSTREAM FROM THE YOUNG GORGE CUT SINCE THE DEPOSITION OF ASH IN THE OLD COURSE OF THE STREAM.



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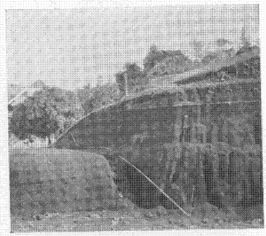

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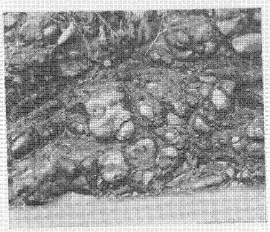
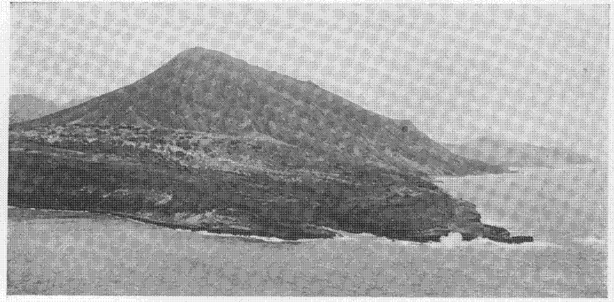


C

D

A, LATE TUFF OF SALT LAKE REGION OVERLYING GRAVEL AND OLDER TUFF IN RAILROAD CUT SOUTHEAST OF AIEA. *B*, BLACK ASH SHOWING GENERAL HOMOGENEITY WITH SLIGHT LAMINATION AND CALCAREOUS CEMENTATION OF CERTAIN ZONES; SOUTHWEST BASE OF ROUNDTOP. *C*, SPHEROIDAL WEATHERING OF TUFF IN DEEPER PART OF PUNCHBOWL MASS, EXPOSED IN CHANNEL OF PAUOA STREAM. *D*, BEDDING OF COARSE AGGLOMERATE SOUTHEAST OF SUMMIT OF ROUNDTOP; THE LAPILLI RANGE FROM ONE TO FIVE CENTIMETERS IN DIAMETER.



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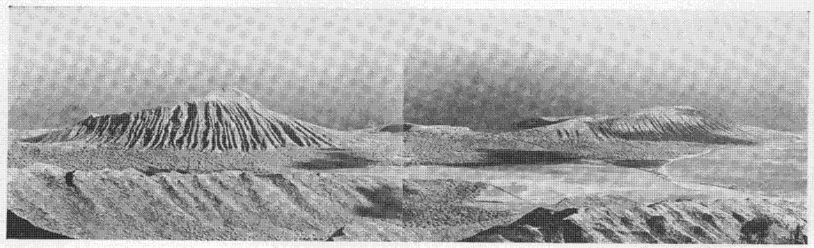
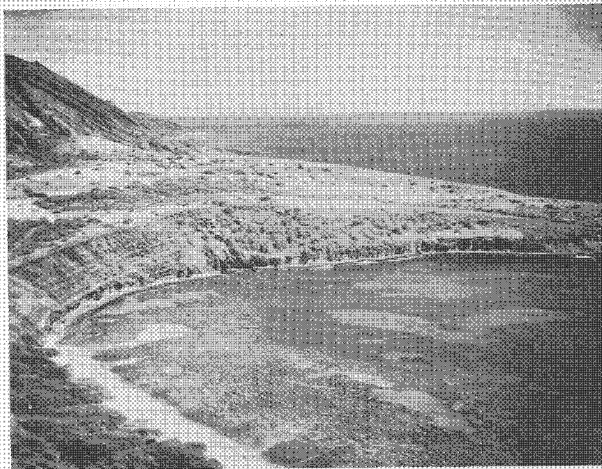


B

A, Koko Crater and east point of Hanauma Bay from the southwest. Makapuu Head appears in the distance at the right and the crest of the Koolau Range at the left. (Photograph by E. Caum.) *B*, Koko Crater (left) and Koko Head (right) from flank of Koolau Range. (Photograph by Oliver Emerson.)



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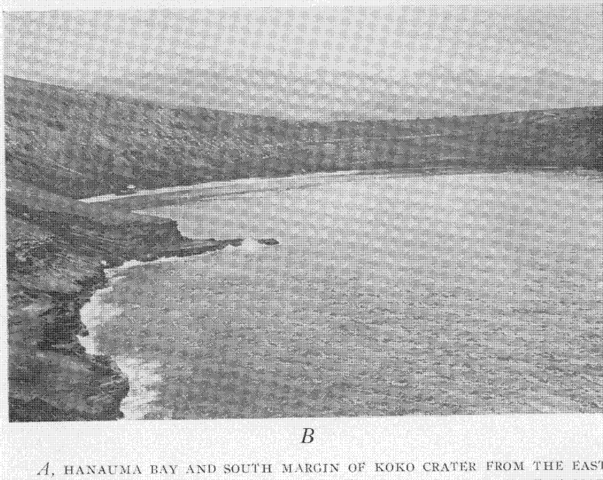
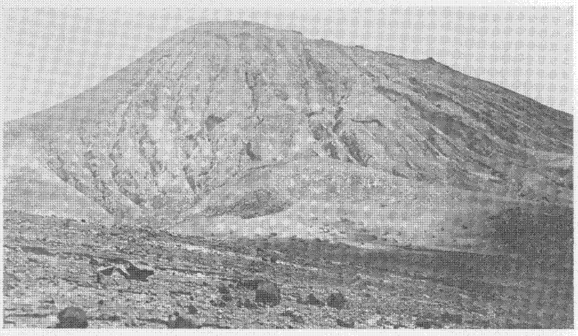


B

A, HANAUMA BAY AND SOUTH MARGIN OF KOKO CRATER FROM THE EAST. IN THE REEF THE LIGHT PATCHES ARE SAND-PAVED POOLS. ROUND THE MARGIN OF THE BAY THE NARROW EMERGED BENCH MAY BE SEEN AT THE FOOT OF THE CLIFF. THE LOW SWALE COVERED BY ALGAROBA TREES JUST BACK OF THE HIGHER PART OF THE CLIFF IS THE VALLEY DOWN WHICH BASALT FLOWED FROM THE KOKO DIKE. *B*, HANAUMA BAY AND KOOLAU RANGE FROM A POINT ON THE WEST MARGIN OF THE BAY. AT THE LEFT A REMNANT OF THE WAVE-CUT EMERGED BENCH CUTS ACROSS THE EDGES OF THE DIPPING BEDS OF TUFF. (PHOTOGRAPH BY E. CAUM.)



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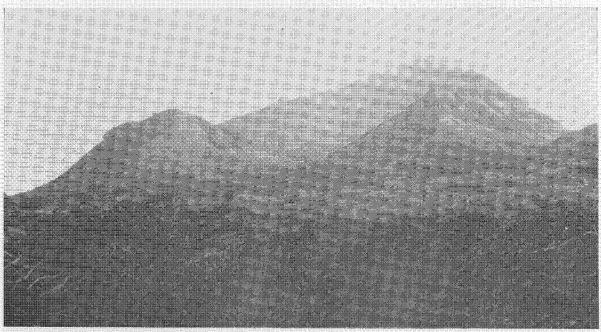
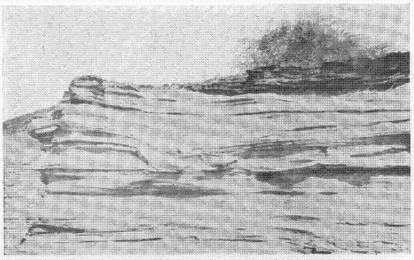


B

A, NEAR VIEW OF KOKO CRATER FROM THE SOUTH. BLOCKS OF BASALT ON THE SURFACE IN THE FOREGROUND FROM THE EXPLOSION CRATER SOUTHWEST OF KOKO CRATER. (PHOTOGRAPH BY H. S. PALMER.) *B*, KOKO CRATER FROM THE NORTHEAST SHOWING THE BREECHED AND STRONGLY ASYMMETRIC CHARACTER OF THE RIM.



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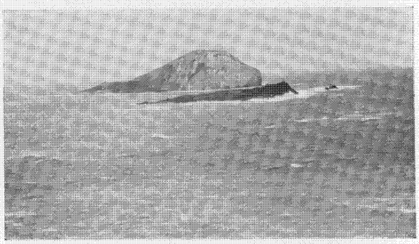

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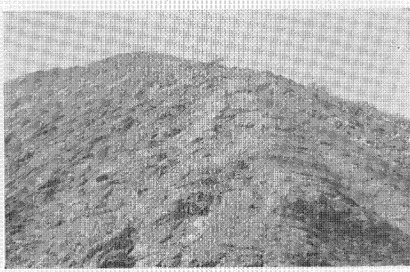
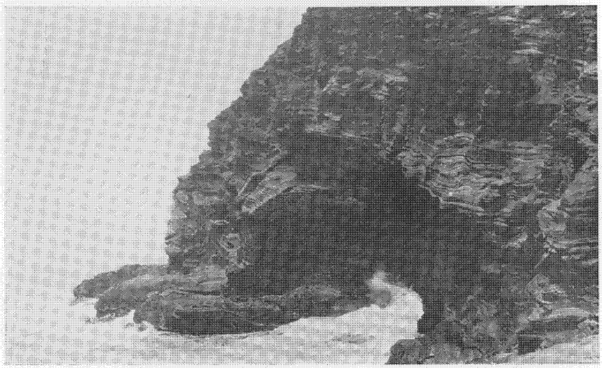


C

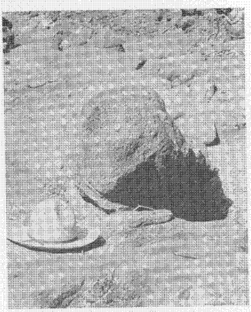
A, TUFF EXPOSURE SHOWING CHANNEL FILLING PRODUCED BY SLUMPING AND EROSION. *B*, MANANA AND KAOHIKAIPU ISLANDS FROM THE KING'S HIGHWAY GAP, EAST END OF THE KOOLAU RANGE. *C*, CRATER WEST OF HEAD OF HANAUMA BAY SHOWING ANTICLINAL STRUCTURE OF TUFF PRODUCED BY PROGRESSIVE MANTLING OF ASH.



A

B

A, WAVE-CUT BENCH AND TUFF BEDDING ON THE SOUTH POINT OF KOKO HEAD. (PHOTOGRAPH BY E. CAUM.) *B*, NORTHWEST WALL OF NONOULA CRATER SHOWING BEDDING OF THE TUFF. (PHOTOGRAPH BY E. CAUM.)



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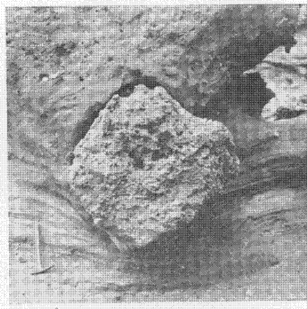

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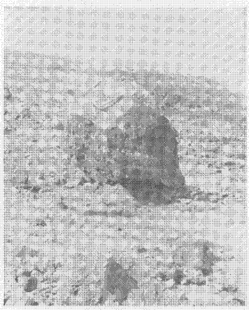

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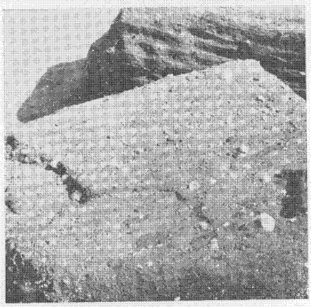
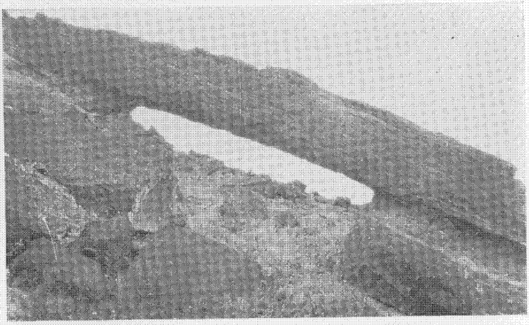


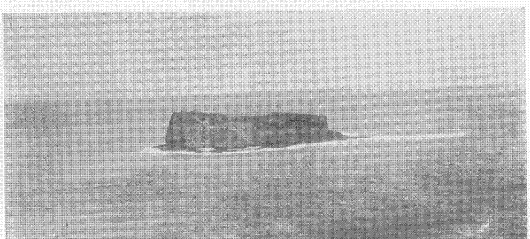
D

A, BASALT BOMB RESISTING CORRASION IN CHANNEL OF SMALL STREAM ON WEST FLANK OF KOKO HEAD. THE BOMB REMAINS IN SITU WHILE THE TUFF HAS BEEN CUT AWAY FROM ITS SIDES. *B*, BOMB SAG BEDDING AND THE LARGE MASS OF REEF ROCK WHICH PRODUCED THE DEFORMATION. SOUTH OF KOKO CRATER. *C*, BASALT BLOCK THROWN OUT BY LATE EXPLOSION, SOUTHEAST SLOPE OF KOKO HEAD. *D*, KOKO HEAD TUFF CONTAINING UNUSUAL AMOUNTS OF CALCAREOUS REEF ROCK. WEST SHORE OF HANAUMA BAY.



A

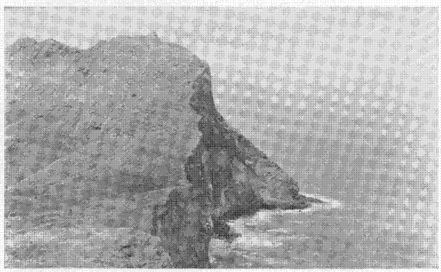
B



C

A, NATURAL BRIDGE PRODUCED BY DIFFERENTIAL WEATHERING OF TUFF, SOUTH FLANK OF KOKO CRATER. *B*, BASALT BLOCKS FROM SMALL FLOW, SOUTH OF KOKO CRATER. *C*, MOKU MANU FROM ULUPAU HEAD.

A



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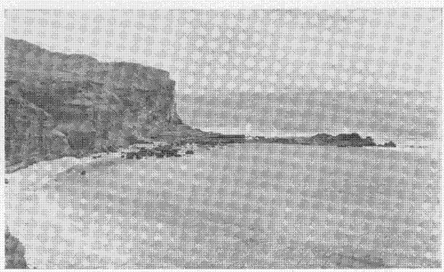
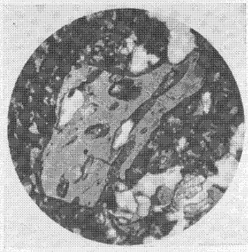
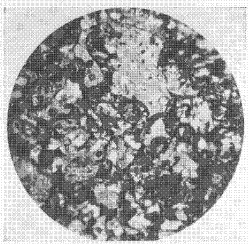


C

A, ULUPAU CRATER FROM THE SOUTHWEST. *B*, SEAWARD FACE OF ULUPAU HEAD LOOKING WESTWARD. HIGHEST PART NEARLY 500 FEET ABOVE TIDE. *C*, KII POINT, EASTERN EXTREMITY OF ULUPAU HEAD, FROM THE SOUTH.

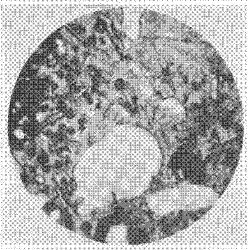

A *B*


C *D*

E *F*

Photomicrographs of basalt and tuff: *A*, irregularly grown and perhaps corroded olivine crystal; with dark margins and reentrants altered to limonite and probably bowlingite; no. 1955, Mauumae basalt, diameter of field 0.8 mm.; *B*, olivine crystal showing zonal extinction; no. 1042, Punchbowl basalt; *C*, vesicular basalt showing alteration of olivine to bowlingite and limonite stain; no. 1985, Rocky Hill, diameter of field 1.2 mm.; *D*, spherulitic filling of a vesicle in porous tuff; the cuspate central portion is calcite, the spherulitic material is thought to be secondary silica, no. 1128, shore of Pearl Harbor, diameter of field is 0.9 mm.; *E*, palagonite tuff; no. 720 b, Koko group, diameter of field 1.5 mm.; *F*, palagonite tuff; no. 1823, Koko crater, diameter of field 1.5 mm.



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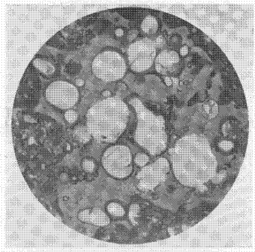
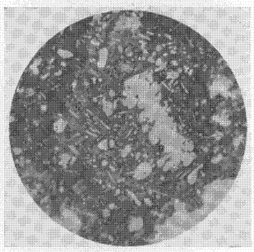


B

C

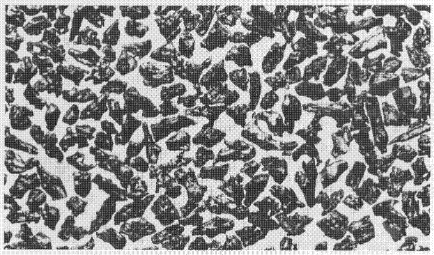


D

E

F

Photomicrographs of tuffs and sandstone: *A*, glass pellet, no. 1852, Koko Crater, diameter of field 1.5 mm.; *B*, glass fragment, no. 1920, diameter of field 2.0 mm.; *C*, glass nucleus of palagonite pellet, no. 1924 c, Koko Head, diameter of field 1.5 mm.; *D*, tuff. no. 3001, Manana Island tuff, diameter of field 3.8 mm.; *E*, tuff. no. 2004, Ulupau Head, diameter of field 1.5 mm.; *F*, beach sandstone consisting mainly of shell fragments and foraminifera with subordinate amounts of olivine from tuffs; the light rounded areas are olivine. no. 96, Diamond Head coast, diameter of field 3.8 mm.



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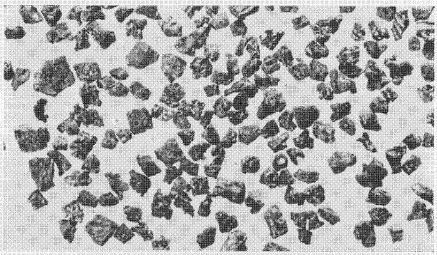

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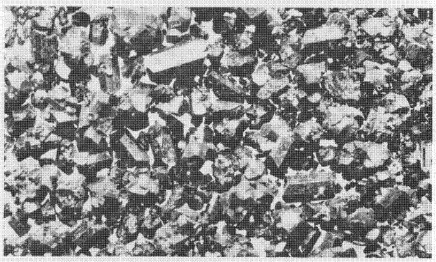
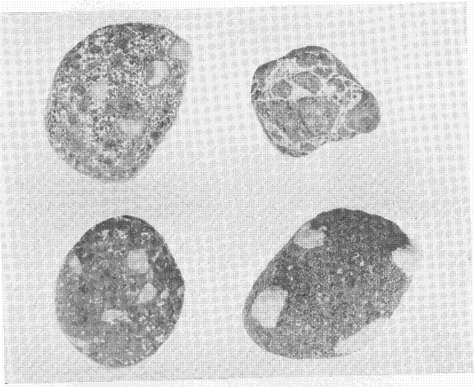


C

A, black ash, no. 515 b, 1-2 mm. grade, east of Punchbowl, length of field 4 cm.; *B*, no. 588, 4-8 mm. grade, Roundtop, length of field 10 cm.; *C*, augite crystals from surface of ground west of Kahauloa crater, Koko district, no. 1987, length of field 4 cm.



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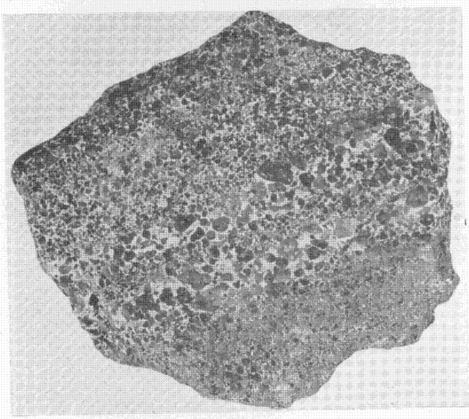

B

A, THREE TUFF PEBBLES FROM MANANA ISLAND SHOWING NODULAR MASSES OF PRIMARY INCORPORATED REEF ROCK AND FINE GRAINED SECONDARY CALCITE AND A PEBBLE (UPPER RIGHT CORNER) OF TALUS BRECCIA FROM THE DIAMOND HEAD BEACH SHOWING DARK MASSES OF TUFF AND A MATRIX CALCAREOUS MATERIAL, LENGTH OF THE LONGEST PEBBLE 7 CM.; *B*, MOTTLED TUFF FROM SALT LAKE; NO. 624 C, LENGTH OF SPECIMEN 11 CM.